Towards inclusive design through constraint modelling and computer aided ergonomics

Towards Inclusive Design through Constraint Modelling and Computer Aided Ergonomics

By

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Abstract

Inclusive Design is a concept that aims to design mainstream products, workplaces, services and facilities that can accommodate or 'include' a maximum percentage of the user population disregarding their age and/or disabilities. The main idea behind Inclusive Design is to design products or workplaces that can be used by all including older, disabled and able-bodied people rather than having two streams of products. There are many social and economic benefits in achieving inclusivity in design such as improving the life of the elderly and disabled people and reaping the profits from the market that extend because of the increased number of consumers. Origins of Inclusive Design go back several decades and are due mainly to the demographic, legislative, and social as well as economic changes that occurred during this period.

This research was conducted to study methods of implementation of Inclusive Design. The research has shown that although there are many advantages of designing for the whole population, designers are reluctant to do this mainly because of the enormity of the task which can take up a huge amount of time and man-power. One solution to this can be found in design tools, which provide the designers with a means to achieve inclusivity relatively quickly and with less effort. Therefore this research has developed a new methodology and a computer tool to assist designers to implement Inclusive Design with ease.

The methodology discussed in this thesis incorporates the physical characteristics of the users of products and workplaces in the design process in order to search for better configurations for designs. It is shown here that by considering the physical aspects of the individual users such as their anthropometry, joint constraints, capabilities etc in a design optimisation process, the percentage user accommodation of a product can be maximised. In order to achieve this, ergonomics analysis methods and mathematical methods were used to interpret user characteristics in terms of design variables and then constraint modelling was used to model the whole design problem and search for better solutions within the constraints of the design.

To implement this method a software tool called SHIELDS was created. This tool utilises the capabilities of four other pieces of software to accomplish the design synthesis. These are HADRIAN and SAMMIE for ergonomics evaluation and MATHEMATICA for mathematical functions fitting and SWORDS constraint modeller to find best solutions. Two case studies were performed to test the functionality of the software and the validity of the methodology developed.

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Chapter 1

Introduction

1.1 Chapter Overview

This chapter introduces the research and the main subject areas and goes on to describe the background to the work. The aims and objectives of the research are also presented together with the research methodology and a brief introduction to the chapters in the thesis.

1.2 Introduction

This thesis is concerned with Inclusive Design concepts and the tools that are used to achieve it. The Inclusive design approach aims to ensure that the products designed can be used by the maximum percentage of the user population, be they disabled, elderly or able bodied. In order to ensure this, products should be ergonomically evaluated at the design stage, giving special consideration to the abilities and disabilities of the elderly and disabled people. When considering the implementation of Inclusive Design, a number of questions emerge. These questions are: what does Inclusive Design mean to product designers and manufacturers? How do Inclusive Design ideas affect the design experience and on the solutions that result? Is there a real need for designing inclusively? What are the major problems faced by the inclusive designer? What can be done to solve these problems and how best to integrate the users in to the design process? (Warburton, 2003).

For the Inclusive Design concept to move forward, it is important to find answers to these questions. Researchers in UK, Europe, USA Australia and Japan perform various researches to achieve this. The research presented in this thesis also attempts to provide some answers to some of these questions by studying the methods of implementation of inclusive design. The primary goal of this study is to find a methodology that would maximise the user accommodation of a product or a workplace. By maximising the user accommodation, it aims to achieve the objectives of an Inclusive Design concept.

Any methodology intending to achieve the Inclusive Design concept must aim to be used by the designers. It is important that these methodologies focus these mostly able bodied designers' attention on the abilities of the older and disabled people. Another important criterion would be that these methodologies assist designers to achieve design inclusivity without expending too much of their expensive time and effort. Educating the designers on the merits of the Inclusive Design will encourage them to wield more effort into designing inclusive products and workplaces.

1.3 A Brief Review of the Inclusive Design Concept

"Inclusive Design" is designing products and workplaces so as not to exclude the disabled and elderly who comprise a significant section of the total user population. New design approaches within the concept of inclusive design are used to tackle this problem. For example Universal Design from the USA (Mueller, 2000), the User Pyramid method (Benktzon, 1993) and the Inclusive Cube (Keates et al, 2001) from Europe and UK. These methods are described in detail in chapter 2.

Whatever the name it goes by, Inclusive Design has its beginnings in demographic, legislative, economic, and social changes throughout the 20th century. The Inclusive Design concept has progressed in the last few decades due to three kinds of changes/advances in the world and has its roots in the public acknowledgement and acceptance of people with disabilities. The three key advances are changes in legislation initiated by the disability rights movement, barrier-free design concepts and improvements in rehabilitation and assistive technology. (www - The Centre for Universal Design, 2002).

All these facts and the increasing globalisation of the market paved the way for products that are attractive to all users. People with disabilities and older people began to demand products to allow them to be more independent and that would give them equal rights. People no longer wanted to use the specialised products that make them stand out from the crowd. The social benefits that can be gained from products that can be used by most if not all people and the economic benefits that can be achieved from the increased market has motivated designers and manufacturers to rethink the design and manufacturing process and this has resulted in the concept of Inclusive Design.

In the true sense of the concept, Inclusive Design attempts to design facilities, products, services and programmes to achieve the maximum inclusion of all users disregarding their physical and cognitive disabilities.

To do this, the needs of old and disabled people are considered together with the younger and able-bodied. Although this applies to all the products and services, designing products to be used for the Activities of Daily Living (ADLs) tasks, are of particular interest when considering older and disabled people (Gyi et al 2000).

ADLs are the activities a person performs for his/her day-to-day living. They can be physical ADLs or instrumental ADLs (Laukkanen et al, 2001). The physical ADLs include self-care activities such as moving indoors and outdoors, eating, dressing, bathing, tying shoelaces etc. Instrumental ADLS are activities such as cooking, shopping, food preparation, using the telephone and handling finances. Many of these activities require a person to interact with the products and equipment in his/her environment, for example, opening/closing doors, windows, taps, using cutlery and driving. These tasks include lever control operations (e.g. doors, windows), taps (e.g. bath, shower, sink), push button controls (e.g. lights, keyboards) and coin swipe operations (e.g. car parks). Many of these tasks are necessary for the daily living of all people regardless of their age and/or capabilities.

1.3.1 Need for Human Anthropometry Data

Designers should have access to information on anthropometry and the capabilities of the whole population of people who would be using a particular design. Although many data bases that are concerned with human capabilities and anthropometry exist, not enough have existed, until recently, concerning elderly and disabled people's characteristics or the actions they find easiest to perform or most difficult. For example, easiest or most difficult shapes to grip, force required to turn or lift something, lowest or maximum height they can reach etc. Those studies that are specific to the old or disabled often have the shortcomings of very small sample sizes and of not being representative of a wide range of disabilities. A useful source to obtain this information can be found in 'Older Adult-data', a handbook published in the year 2000 (Smith et al, 2000).

Together with these data, the designer should also have access to 3-D information concerning people, including their size, functional reach, vision, cognitive abilities and strength and the predictions of the range of postures the people would adopt in order to perform the specific tasks. Human modelling systems such as SAMMIE (SAMMIE is a man modelling software which provide facilities for ergonomics evaluation of workplaces) (Case et al, 1990), JACK (Sundin et al, 2000) and SAFEWORK (Fortin et al, 1990) provide some of this information as 3-D models of people and increasingly designers use these 3-D computer modelling systems to visualize and develop the physical aspects of their design work.

To predict the percentage physically accommodated by a design a multivariate analysis considering a number of body dimensions and capabilities simultaneously is required. For example, a person should be able to achieve access to a product or workstation, be able to see any displays or instructions, understand them and have the reach, mobility and strength to operate the various controls. This requires data of all the body dimensions of that person, e.g. arm length, leg length, height, seated height and cognitive abilities as well as the dimensions of the product. Also more importantly, all these aspects need to be considered simultaneously.

1.3.2 A Historical Perspective of Human Data

Anthropometry deals with human body measurements, particularly with measurements of body size, shape, strength and working capacity (Pheasant, 1996). Artists and sculptors have employed what is known as 'human scale' and 'human proportion' since ancient times. Even the tomb painters of Ancient Egypt, although they only worked in elevation and not in perspective as shown in Figure 1.1, have divided the standing figure into 14 equal parts to be drawn on a modular grid, where the grid intersections corresponded to certain predetermined anatomical landmarks. These modular systems and mathematical ratios were employed for drawing purposes as simple drawing aids.

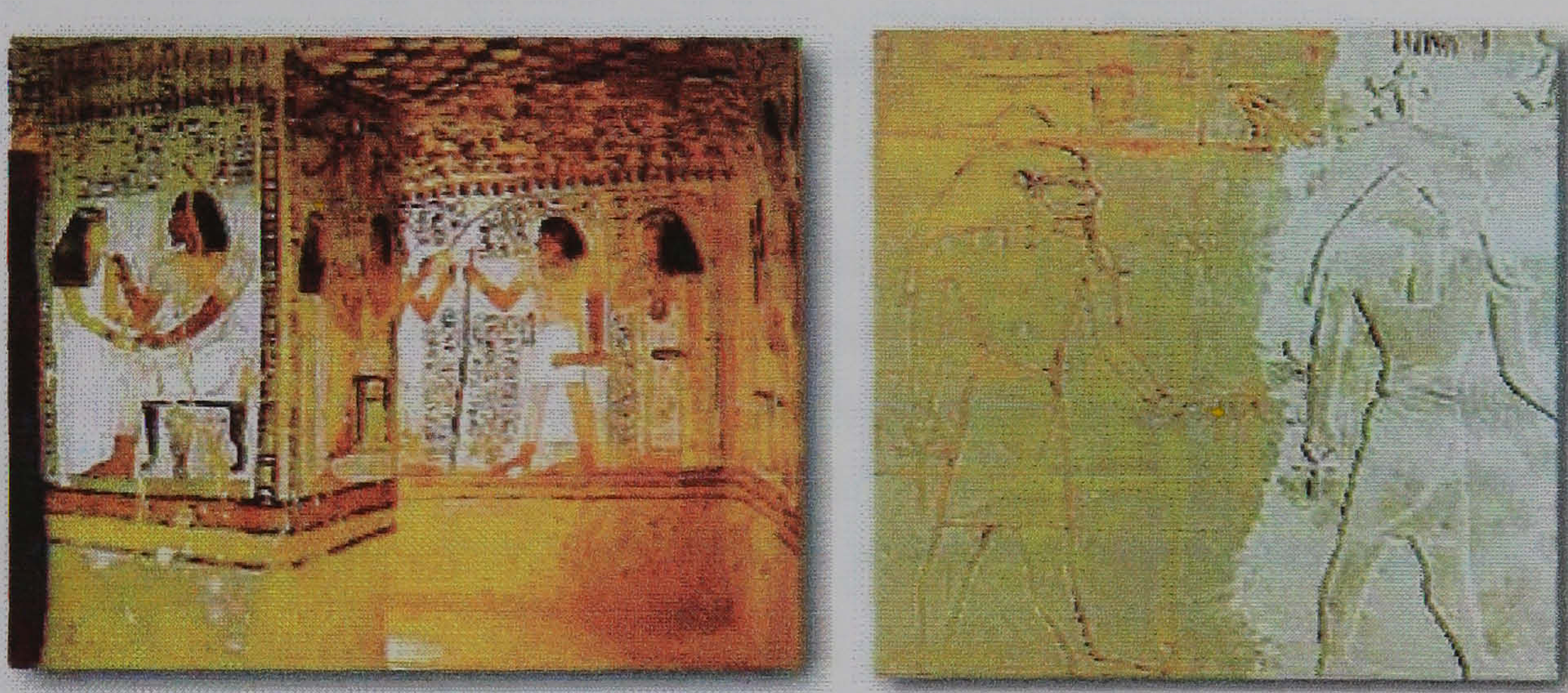


Figure 1.1 - Pictures showing ancient Egyptian paintings

In classical times, people thought that certain whole number ratios between dimensions of the body and its parts were aesthetically pleasing and indeed many of the drawings and sculptures created using these ideas are exquisite. However, no record can be found of many of these systems of human proportions. The most detailed system of human proportions that survived from that time is that of the Roman architectural theorist Vitruvius in a year around 15 BC. His theory stated that ' the stature of a well-made man is held to be equal to his arm span' etc. This theory was illustrated by Leonardo da Vinci (1452 – 1519) in his famous drawing of the 'Vitruvian Man', in which a male figure is drawn circumscribed within a square and a circle. A picture of this original drawing by Leonado is shown in Figure 1.2.

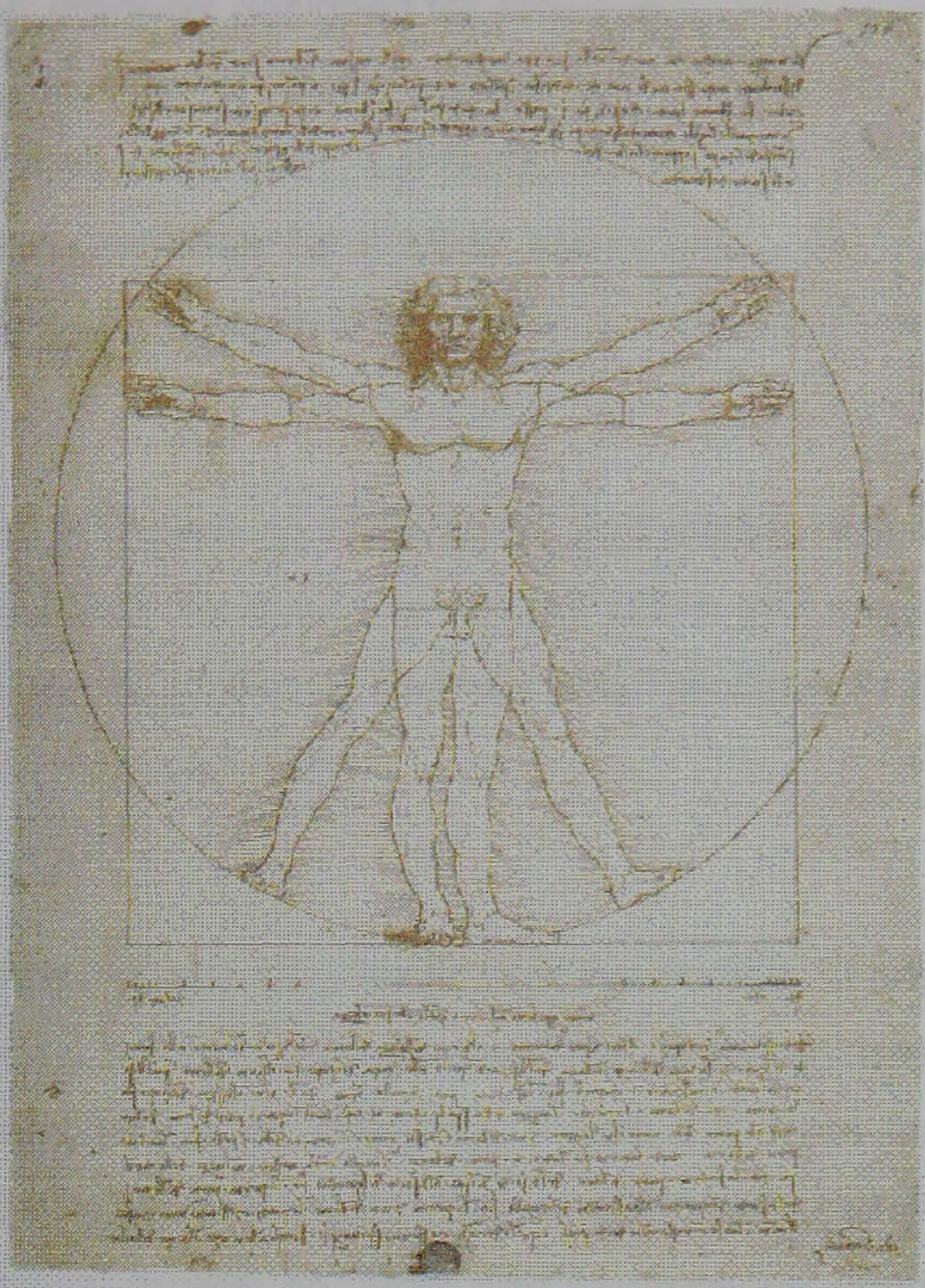


Figure 1.2 - Leonado da Vinci's 'Vitruvian Man' (www – The Art Prints on Demand, 2002)

By Leonado's time, another theory called 'golden proportion' or 'golden ratio' had also come into existence. This theory stated that 'the umbilicus divides the stature of the standing male person in the golden section, that is, such that the ratio of the greater part to the whole is equal to that of the lesser part of the greater part'. This was used in drawings, sculptures as well as in architecture, which was known as 'designed to the human scale'.

These ratios were very aesthetically pleasing because the human eye tends to find beauty in well-proportioned and symmetrical objects. However, in reality humans do not have these proper proportions, except on rare occasions. Correlation between individual's measurements is very poor and over the years many research studies have been conducted to collect and present these anthropometric measurements and hence to overcome this difficulty.

1.4 The Importance of Inclusive Design

The Inclusive Design approach was originated in contrast to the design for the disabled approach where products are designed to meet the special needs of disabled people, and are only used by those people with special needs. On the other hand disabled people cannot use many other products designed for able-bodied people. Many of these products are necessary for Activities of Daily Living (ADL) and are needed for personal independence (Laukkanen et al, 2001, LaPlante, 2002). ADL activities are the necessary activities that a person performs for his/her daily living. ADL tasks include self-care activities such as bathing, food preparation, cooking, shopping as well as leisure activities.

At the beginning of the 20^{th} century, older adults and people with disabilities were a true minority. The average human life span was only 47 years, and people who received spinal cord injuries had only a 10% chance of survival. Most people with chronic conditions lived in nursing institutions (Story et al, 1998).

Now, as a result of better nutrition and health care the number of people aged 75 and over is forecast to double over the next fifty years and as disability increases with age a large number of disabled people can be expected. Figure 1.3, from the US Census Bureau (McDevitt, 1998), shows huge increases in the population of ages over 65 in almost every region of the world. Actual figures for 1998 and extrapolated figures for 2025 show this increase clearly and especially for the developing world where the facilities for the disabled and older people are still emerging.

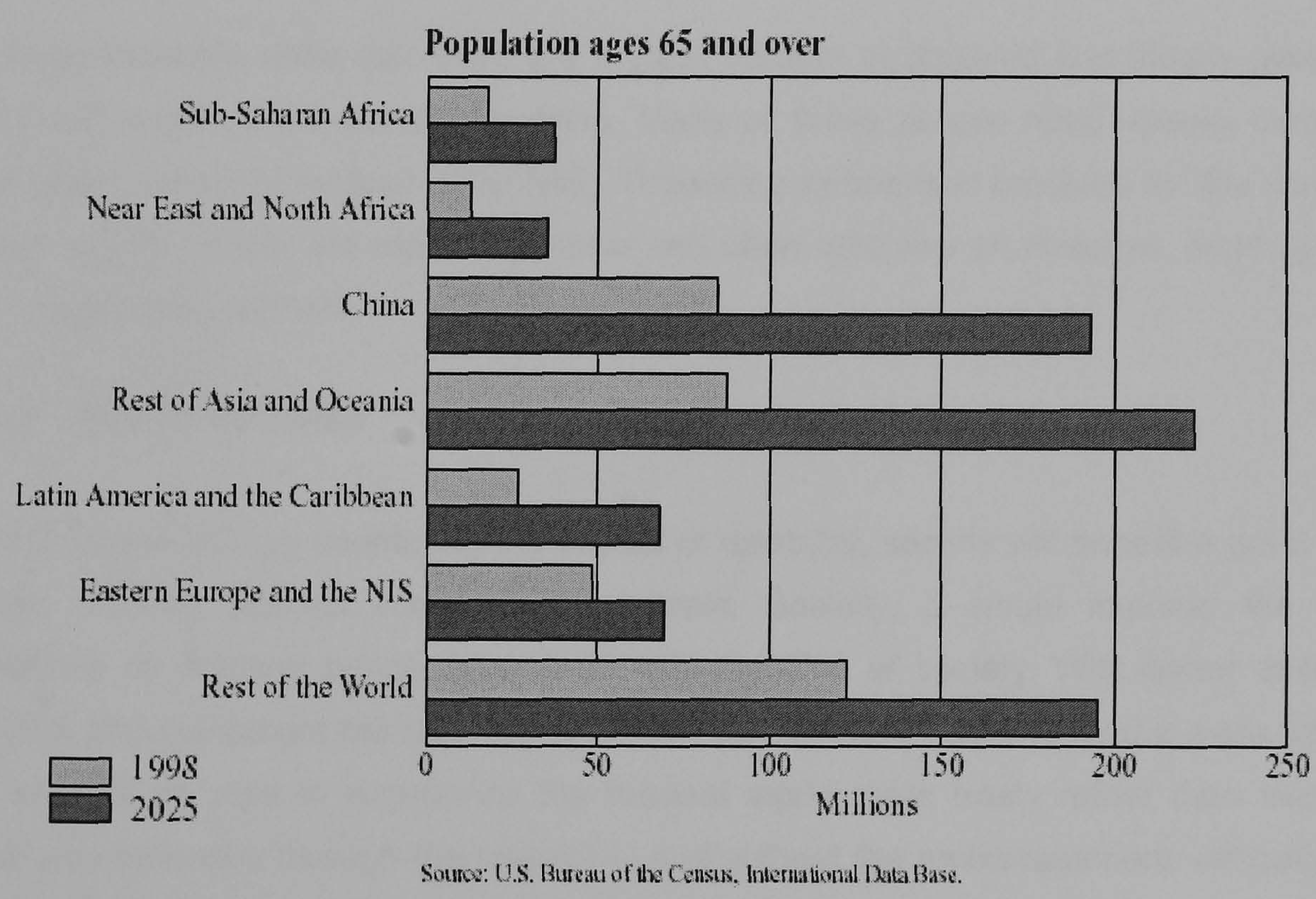


Figure 1.3 - Aging Population (McDevitt, 1998)

Antibiotics and other medical advances enable people to survive accidents and illnesses, which were previously fatal. At the end of 1994, 20.6% of the population in the United States had some level of disability and 9.9% had a severe disability (Story et al, 1998). The introduction of equal opportunity and/or anti-age discrimination laws in most of the economically developed countries has resulted in an increased number of elderly workers in the workforce (Kothiyal et al, 2000). Elderly and disabled drivers are also becoming an increasingly large proportion of the motoring public.

Smith and Twomey (2002) report that according to Labour Force Survey data in UK, in autumn 2001, nearly one in five people of working age in private households had a long-term disability (3.7 million men and 3.4 million women). Around three and a half million disabled people were in employment, an employment rate of 48% compared with a rate of 81% for those without disabilities.

The Social Survey Division of the Office for National Statistics in UK, has published the findings of the Census 2001 which they claim is 'the most comprehensive survey of the UK population' in their website (www – National Statistics online). Census 2001 shows the trends and implications of the ageing society in England and Wales. According to that there are 336 000 people who are 90 years and over living in England and Wales. It also shows that single-pensioner households make up 14.4% of all households, but more than two-thirds of these (68.2% or 2,129,000 pensioners) have no access to a car. More than half of women aged 75 and over live alone, which include 52.5 % of 75-84 year olds and 54.5% of 85 year olds and over.

All these statistics show that there are a great number of disabled and elderly people in the world and that the number is rising. Many of these people need special care and specialized products for their daily living. Producing specialized products for the disabled and/or elderly people are more expensive and often relatively unattractive, especially for the people who use them.

1.4.1 Social Benefits

All this means that by countering the impact of disability, society will benefit a great deal. These benefits can be social and economic. Socially, it would improve the living conditions of disabled people and hence the condition of society. With better designed facilities and equipment the disabled and older people will be able to lead a more fulfilling life and will be able to experience the modern world more freely rather than living on other's experiences through the television, and without the embarrassment, difficulty and expense of using specialized equipment and services. They will be able to live independently and have a more active social life. Living independently is especially important to older people who are able to remember what it was like to be free and independent. More importantly, using the same products as able-bodied people will remove the stigma disabled people may feel when using products that are made especially for the disabled. This would help them to be more comfortable in the society.

1.4.2 Economic Benefits

Economically, designing products that can be used by disabled, elderly and able-bodied people will certainly save a large amount of money otherwise needed for specialized products. This would not only lighten the burden on society but it would also generate considerable business opportunities by extending the market capacity and by being able to exploit the global market. Although it can be said that the globalisation of products makes products designed for the disabled more profitable, this profit will be relatively small compared to a profit from the global market for a product that can be used by all. Added to this, disabled and older people are becoming a significant force in the market. It has been estimated that 36 million disabled people in the U.S. spend 40 billion dollars on special products and the population over 50, which includes most middle-aged people, purchase 60% of all domestic cars and own 50% of all homes (Steinfeld 1994). Despite this increased economic power, many gaps exist in the market concerning the disabled and elderly.

1.4.3 Benefits for the Developing Countries

Another important factor can be found in the developing countries, where assistive technology is more costly, and the governments also have a need to control public welfare costs. Assistive technology, which is described in detail in chapter 2, is the technology that has been developed in order to assist people with disabilities. In these situations, instead of using assistive technology for the disabled, the Inclusive Design concept can be applied because it can be more generally available at a lower cost than assistive technology or specialized products.

All this provides immense motivation to develop methods to achieve Inclusive Design.

Although there will always exist a need for highly specialized products, the benefits that could be gained by designing and producing products that can be used by a larger user population disregarding their abilities and disabilities far outweigh the effort that needs to go into designing and producing them.

1.5 Need for New Design Tools

Designers who are willing to adopt the Inclusive Design approaches and also designers who have been commissioned by their clients to use Inclusive Design approaches must have the necessary tools to work with. This is especially true when considering the challenges they have to face while trying to achieve these new ideas of including most, if not all, of the user population in a design.

These designers must consider the user population at the beginning of the design work. However, typically designers do not involve users until the product is near completion or else they only involve a few users who may not reflect the variety of different users (Gyi et al, 2000). For designers to be able to consider the users in an inclusive design approach, a large amount of data regarding disabled and elderly people should be available.

Added to this, if designers have access to CAD/CAM packages and human modelling software that can be used to perform ergonomic evaluations, their task would become easier and less expensive and would allow them to model those users who are difficult to involve in testing procedures. Currently, most designers use at least one CAD/CAM package and many use more than one mainly because no single package meets all their needs (Pankhurst, 1998). Ergonomics and CAD packages are usually separate pieces of software and designers need to have access to both in order to evaluate a design with regard to the users.

If the design problem was formulated properly, by considering the users and the parameters of the design, a design that maximises the user accommodation can be synthesised from the existing data of the design. This indicates that a solution to this design problem may lie in design optimisation techniques and ergonomic evaluation of products or workplaces.

An important factor in the inclusive design process is that the aspects of users of products and workplaces must be incorporated in it to achieve inclusivity. Therefore there is a need to develop techniques to assist designers to achieve Inclusive Design objectives by finding techniques to incorporate the user in the design optimisation process. These techniques should introduce the user almost at the beginning of the design process to make the design a truly a user centred one.

This could be an enormous task for designers to tackle manually. However if there were tools that use the above-mentioned techniques they could prove very effective. This would generate a need for software tools to be used to model humans with varying degrees of abilities and sizes and that can be used for ergonomics evaluations. A potentially more useful, time saving and cost effective software technique would be a technique that is able to predict the design parameters to maximise the user accommodation. Such a technique would alleviate the need to build costly models as well as user trials involving disabled and elderly people, which can be a great inconvenience for them.

1.6 Myth of Designing for the Average Person

Hertzberg presented a study that discusses this poor correlation between human body dimensions as far back as 1960. It was shown that the 'average man', for whom many designers design products even today, does not exist. Hertzberg (1960) has reported findings of a study made around 1952 by Daniels and Churchill. In that study, the body size data were examined for more than 4000 flying personnel to see how many men could be average in 10 dimensions. The 'average' was taken to be plus or minus 15 percent from the average. This was called 'approximate averages' and was used in each dimension. It was shown that if only one dimension (e.g. stature) was considered there are only 25.9% average people and if 2 dimensions were considered average people were only 7.4% and if 4 dimensions were considered this figure dropped to 1.8%. No average people could be found in a sample of over 4000 men, if 10 dimensions were considered.

Even if this mythical average person did exist, designing for that person would effectively design out 50% of the user population. For example, if a doorway were designed for the person with average stature, all the people taller than that, which is half the user population, would be banging their heads on the doorframe.

After establishing that the average person does not exist, and that by designing for the 'average' person would exclude half the population, designers are faced with the problem of finding an efficient method of including the human dimensions for design. The concept called 'design limits' or 'range of accommodation' system presents such a method. In this system, an adequate sample of the user population is selected and from them all the relevant dimensions for the design are taken. From these necessary data, the dimensions for the workplace are chosen according to the percentage of the population that the product intends to accommodate. This method is very valuable when designing products to be used by older people, disabled people and able-bodied people. However, one disadvantage of this method when considering these groups of people is that these population data do not necessarily represent the individual users.

Traditional anthropometric and biomechanical studies report data using percentile values which is a very simple statistic and is univariate and with respect to only the population for which they are created. These anthropometric data are presented as data tables, human figures or computer models.

In order to design for the whole user population, including the disabled and the elderly, the focus of the design should specially be on the multivariate issues such as access, fit, reach, vision, strength and posture. Multivariate data is data taken simultaneously on many variables. This is opposed to univariate data – which is data taken on a single variable – and is a big issue in the concept of Inclusive Design. Even when designing only for able-bodied people, if the design is not a one-dimensional problem, such as the height of a doorway, there are many variables to consider. Since most designs involve several dimensions, it is essential that relationships between them are understood.

For example, designing a car seat involves knowledge of the driver's leg length, eye height, arm length etc. Usually anthropometric data for such designs are taken only for the 5^{th} percentile woman and 95^{th} percentile man on the assumption that this would accommodate 95% of the user population (Haslegrave, 1986). Since correlation between body dimensions is relatively low (Hertzberg, 1960), it is not valid to assume that all dimensions of the 5^{th} percentile woman are the 5^{th} percentile value for the female population. The same applies to the male population.

Therefore when evaluating reach, fit, vision etc, many variables in the user population such as stature, weight, sitting height and eye height. should be considered as well as the variables in the design. Together with these, other variables such as constraints to joint movement, and reduced strength of disabled and older people should also be taken into account.

This evaluation can then be used to predict the percentage of users that can be catered for in a new design. The ability to predict who has been designed out is also an important aspect of the Inclusive Design approach because then the design can be modified to include the designed out users.

1.7 Research Aims

The overall aim of this research is to study methods for the implementation of "Inclusive Design" so as to improve the percentage accommodation of designs that include elderly, disabled and able-bodied people and to develop a new approach to increase the user accommodation of a product or workplace.

1.8 Research Objectives

1.8.1 To study Inclusive Design concepts and the existing methods used for its implementation, study the products and services designed using these techniques and investigate the characteristics of the users and product design techniques to discover if a significant improvement can possibly be made.

1.8.2 To establish a methodology that would search for better solutions of a product design in order to increase user accommodation of a design by considering the characteristics of all its individual users including disabled, older and able-bodied people.

1.8.3 To build a prototype software system to implement the above developed method.

1.9 Sub-problems

Sub-problem 1:

Can a user's physical capabilities and constraints, e.g. joint constraints; be adequately structured in a mathematical form to facilitate their use in an optimisation problem?

Hypothesis:

If a user is unable to use a product or workplace because for example, it is out of reach, changing the parameters of that product or workplace and evaluating it with a computer model of the user will produce a value for this failure, for example the out of reach distance. For each of these failure positions it is possible to generate a path for this inability and that path can be mapped into a mathematical expression.

Assumption:

Since the Inclusive Design problems evaluated are real life problems, the above 'inability path' would not follow a known mathematical expression. Hence expressions that fit these paths as closely as possible need to be established.

Sub-problem 2:

Can the Inclusive Design Synthesis problem, which requires maximisation of the user accommodation, be constructed as an optimisation problem that takes into account the users' physical factors as well as the constraints of the product or workplace in order to search for better solutions using optimisation methods?

Hypothesis:

All the factors required for the optimisation of physical aspects of a design concerning the users and the product or workplaces can be expressed as mathematical functions enabling them to be used in an optimisation process with any other constraints that affect the product.

Assumption:

To simplify the optimisation problem only the physical aspects of the users and the design are considered. Cognitive aspects of the users and such things as aesthetics of the product or workplace are either ignored or assumed to be taken into account at a different stage of the design process.

Sub-problem 3:

Can a fully functional software system be created to model, evaluate and solve the Inclusive Design Synthesis problems using existing software?

Hypothesis:

The Inclusive Design Synthesis problem can be structured in such a way that it can be implemented in a software system to ensure it being evaluated and practically formulated in a soluble optimisation process.

Assumption:

It is assumed that the database of individuals found in the software used represent the users of the evaluated products.

The above sub-problems and assumptions were made chiefly to clarify and focus the research. It is acknowledged that in human related studies it is not always possible to justify all the required assumptions or to test each aspect using scientific methods. This is mainly due to the unpredictability of human behaviour and capabilities. In this research, two case studies were performed to test the hypotheses.

1.10 Scope of the Research

This research spans the subjects of Inclusive Design, ergonomics, and numerical optimisation and software development. Each of these subjects covers a huge area and within the limitations of resources and time only those elements that are essential to the project under discussion were considered.

This research was limited to studying users' physical capabilities such as reach ability and vision and their physical characteristics such as anthropometry details and joint constraints, when interacting with products and workplaces. Many other factors such as cognitive capabilities and strength factors have been ignored.

An attempt was made to find better solutions for the layouts of workplaces like the kitchen that would maximise the user accommodation. Theoretically the optimisation process established in this research is capable of utilizing the objective functions or cost functions that affect the product's size, cost, material usage etc but they were not tested practically. The practical work was limited to the re-layout of designs, which contained several objects within them.

The research takes into account only the physical aspects of products and workplaces, such as the size and position of objects. It is not concerned with other design factors such as, aesthetics, ease of cleaning, product desirability and materials used. Also other Inclusive Design areas such as services or facilities provided are not considered.

1.11 Research Methodology

This research has developed a method that can be utilised in order to implement Inclusive Design concepts by finding better solutions to design problems that maximise the user accommodation. The conceptual basis was developed through a literature review of the Inclusive Design concepts, the existing methods of implementation of Inclusive Design concepts, the technology available to develop a new method and the general approaches that can be utilised in developing a new method.

A review on ergonomic evaluation software methods of products and workplaces using computer generated human models has been carried out. A new approach of using individual data rather than population data of the users of products has been used in the study. Optimisation methods that are able to handle large amounts of data were studied to select a suitable method to use with the multivariate data generated when workplaces are evaluated with individual users. The capabilities of many human modelling software tools were also investigated.

The methodology developed in this research utilises users' physical characteristics and the physical aspects of products or workplaces in a constraint modelling process to optimise products and workplaces. A prototype software tool was created to implement and to demonstrate this method. This software is to be used by designers as a tool to aid in their quest to achieve Inclusive Design concepts and they are not expected to have a specialised knowledge of ergonomics or optimisation methods to use the software.

The software system has been implemented by means of existing software techniques and products such as Microsoft Visual Basic and MATHEMATICA. It also uses another software tool called HADRIAN (Marshall et al, 2002) and the constraint modeller SWORDS (Mullineux, 2001) both of which have been obtained from their respective developers in Loughborough and Bath Universities.

Two case studies were developed to test the methodology developed in this research and the new prototype software tool.

1.12 Thesis Structure

This thesis consists of eight chapters including this introductory chapter. The content of the chapters are given below:

Chapter 2: Implementation of Inclusive Design

This chapter provides a review of Inclusive Design and various methods that are being used to implement Inclusive Design. The main problem areas in the implementation of Inclusive Design are identified and stated. The approaches developed to answer the basic problems in Inclusive Design implementation are discussed. The applicability of Inclusive Design concepts in practical design environments and the challenges in developing effective methods to achieve the Inclusive Design concept are also discussed.

The methods and tools that can be used for Inclusive Design applications are analysed to select suitable method and tools for the development of a new methodology.

Anthropometric details of the users of the product or workplaces and their capabilities are briefly reviewed.

Chapter 3: Constraint Modelling and Computer based Human Modelling Systems

This chapter mainly focuses on the technical issues of the selected methods and tools. Three areas for evaluation of products and workplaces, namely, reach, fit and vision are also identified and discussed. The software tools used in the research are discussed separately. Their capabilities and limitations are also discussed.

Chapter 4: A New Methodology for the Optimisation of Physical Aspects of a Design

This chapter discuss the method developed in the research to optimise the physical aspects of a design with respect to its users. Particular attention was given to the details of the general optimisation model created and how to incorporate the individual users in it. Constraints of the design and objective functions for the optimisation process are also discussed.

Chapter 5: Software Design and Modelling

This chapter presents the developmental and implementation details of the software system that uses the theory proposed in the previous chapter. The architecture of the prototype software application, 'System for Human Interaction Evaluation and Design Synthesis (SHIELDS) is outlined. The first stage of the development of the prototype application to test the functionality is described. Limitations of SHIELDS are discussed and potential future work is outlined.

The practical details of the software design are also presented and the software components used are described in detail. The limitations of these pieces of software and methods to overcome or avoid the difficulties to obtain the desired results are discussed. The user interface is also discussed.

Chapter 6: The ATM Case Study

A case study involving an automated teller machine (ATM) is presented in this chapter. It is described in the context of the developed software mainly and the results obtained are analysed and discussed.

Chapter 7: The Kitchen Case Study

This is a more complex case study that put the developed method under scrutiny. How the software and the method is able to handle a workplace with a large number of objects is studied and the results analysed and discussed.

Chapter 8: Discussion and Conclusions

This chapter summarises the research work presented in this thesis. The methods developed and the capability of the software tool, are discussed. The main conclusions and the research contributions are stated. The limitations of the research work and future work needed are also described.

Chapter 2

Implementation of Inclusive Design

2.1 Chapter Overview

Inclusive Design is a relatively new concept and in this chapter an effort has been made to present the work that has been done in this area and to identify a gap in the current practices. Then the chapter will present an overview of the existing methods, technologies and software that can be used to solve the research problem. In addition, currently existing data and research concerning the elderly and the disabled people are presented. In so doing, it is hoped to highlight the significance of the research undertaken and to discuss relevant issues pertaining to the research topic.

2.2 Inclusive Design Concept

Inclusive Design in a nutshell is designing a world that works for everyone regardless of ability. Where special products are absolutely necessary Inclusive Design aims to design products that would offer people as much dignity and enjoyment as possible. Inclusive Design or Design for All emerged in UK and other European countries from collaboration between industry, designers, researchers and educators (Coleman, 1994). Its main focus has been social inclusion whereas its counterpart in US called Universal Design focuses on individual rights.

These approaches acknowledge the fact that people differ in various ways and recognises that any particular disability is simply another way in which people differ from each other (Jordan, 1999). It is also aware that the designs that suit people with particular disabilities may also bring advantages to people without disabilities. For example, the ballpoint pen and the television remote control were originally designed for people who have disabilities with the hand or with movement but they have now become everyday products for everyone. As aptly stated by Sandhu (Sandhu, 2000) Inclusive Design or universal design is an approach that 'values and celebrates human diversity'.

This concept forces designers to move beyond ergonomics and to rethink the traditional assumptions of abilities and disabilities. Traditionally people are labelled as disabled because of their physical or mental state and the fact is ignored that people's capabilities are dependent on the changing states of health, accidents, tiredness, ageing, pregnancy and also that it is affected by the things people are doing e.g. pushing a wheelchair or carrying shopping (Coleman, 1999). Most disabilities are man-made and arise out of the mismatches between people and their environment. This environment more often than not consists of poor design and these disabilities can be overcome by good design.

Inclusive Design or universal design is different from accessible design. Accessible design as described below is only for the disabled people and is concerned with making products and buildings usable by people with disabilities. On the other hand, Inclusive Design products and buildings are accessible and usable by most of the population including the disabled and the elderly. Accessible design has a tendency to lead disabled people to separate facilities e.g. a ramp set off to the side of a stairway at an entrance or a wheelchair accessible toilet stall. Inclusive Design on the other hand provides a solution that can accommodate all the population including the people with disabilities. An entrance that is designed to be 'inclusive' would not have stairs at all. Not only that, Inclusive Design would also consider young people, older people, right and left handed people, men, women as well as disabled people. This process would also find solutions for people who have limitation but are not disabled. For example, people who cannot read or people who have a phobia for high tech equipment.

2.2.1 Changes in the Design Professions and the Implication for Inclusive Design

The design professions are changing irreversibly and this will have a major affect on the concept evolution and practice of Inclusive Design (Sandhu, 2000). These changes are things such as designers working increasingly in the service sector due to developments in information technology. They are now able to use the power of telemetrics and can access databases for various information and images. Due to these developments, divisions between various design professions have become hazy. Another change is that the designers are becoming very adept at integrating software and hardware interfaces into a wide variety of products such as smart equipment and smart homes. This developed and highly knowledgeable designer who can access a wide range of information of products and people will be equipped to further the concepts of Inclusive Design.

2.2.2 Inclusive Design versus Specialised Design

Rehabilitation engineering and assistive technology emerged in the middle of the 20th century with the return of thousands of disabled veterans from World War II in the 1940s (Story et al, 1998). Assistive technology is the technology applied to devices for personal use created specifically to enhance the physical, sensory and cognitive abilities of people with disabilities and to help them function more independently in environments oblivious to their needs.

Rehabilitation engineering became a specialty that applied scientific principles and engineering methodologies to other technological problems of rehabilitation including communication, mobility & transportation. The technology developed in this way has potential in the application of Inclusive Design.

The Centre for Assistive Technology (www – Centre for Assistive Technology, 2001), is a US research institution based at the University at Buffalo, State University of New York. This Centre promotes research in assistive technology. It has developed several products for the use of elderly and disabled people such as the rising activity chair and an articulating positioning device.

As seen from these examples, rehabilitation engineering and assistive technology target only the disabled population. The products created are highly specialized and hence neither suited nor intended for the able-bodied people and these products do not attract them. The investment in research and development for some disability products is sometimes disproportional to the return from the product (Etchell, 1999). This creates an obvious need for another type of technology, which is able to cater for all these different groups.

2.3 The need for Inclusive Design

The answer to the question 'why is it necessary to accommodate the Inclusive Design concept?' can be found by observing the changes that have happened in the world during the 20th century. The greatest achievement of that century was the increase of life expectancy of the people. As Kirkwood (1999) points out, since 1900, UK life expectancy has increased on average by 2.5 years per decade. Together with this, people's thinking patterns and legal requirements have also changed. Apart from the social benefits that can be gained by designing for inclusivity, the economic benefits and the legal requirements from various governments in the world have also been great incentives for Inclusive Design approaches.

2.3.1 Changing Demography – Ageing Population and the effects of Ageing

Increase of life expectancy, reduction in infant mortality and long-term falls in birth rates have generated an ageing population in the world, especially in the developed world (WHO, 1998). Coleman (2003) shows that from the early 19th century, the proportion of the UK population aged 60 and over rose from under 10% to more than 35%. Across the European Community (EC), it is estimated that by 2020, close to 50% of the adult population will be aged 50 and over while 20% of the population in US and 25% of the inhabitants in Japan will be over 65 (Coleman, 1993). This trend is evident to a lesser degree in the developing countries like Mexico and India. Also due to strict policies that control the birth rate in China the shift towards an aging population there is accelerating (WHO, 1998). Japan is now the 'oldest' of all populations, due to dietary and other factors that favour longevity (Coleman, 2003). Japan is expected to have a quarter of the population aged 65 years and over in 2014 (Kose, 2003).

Being able to live longer is in itself a wonderful fact for all. However urgent need for the reinterpretation of the life course arise as a consequence of changes in lifestyle and activity. In the past, the main focus of design, both of products and environments, has been the working population, which has been mainly young and able-bodied. With the increase of the ageing population it is necessary to consider the effects of ageing and what it does for the abilities of the people. An important fact to remember is as Coleman (2003) aptly put it 'people don't lose their ability or desire to make choices just because they are older'.

2.3.1.1 Ability Losses in the Older Population

Grundy et al (1999) present the results from the 1996/1997 disability follow-up survey to the family resources survey and describe that 20% of the total population in the UK had a disability and that 48% of the disabled population were aged 65 or older and 29% were aged 75 years or more.

For the inclusive design approach, the range of user capabilities rather than disabilities is of most importance (Clarkson et al, 2003). This is because the user/product interaction requires a match between functional demands made on users by products and the capabilities the users exhibit. Clarkson et al (2003) points out that the high capability demands from the products and the lack of relevant capabilities among the users often account for design exclusion.

The above-mentioned survey has adopted seven capabilities that are particularly pertinent to product evaluation. They are: locomotion, dexterity, reach and stretch, vision, hearing, communication, and intellectual functioning (Grundy et al, 1999). A summary of the results of this survey is presented in

Figure 2.1 and Figure 2.2 for the 16 to 49 years old and 75+ years old populations. The most significant feature of these graphs is the magnitude of scales used. Although the graphs have similar distributions, the percentage of those with a loss of capability in the 75+ age band are 10 times higher than for the 16-49 band. This shows that in all the surveyed capabilities, the loss of capability is higher when people are older.

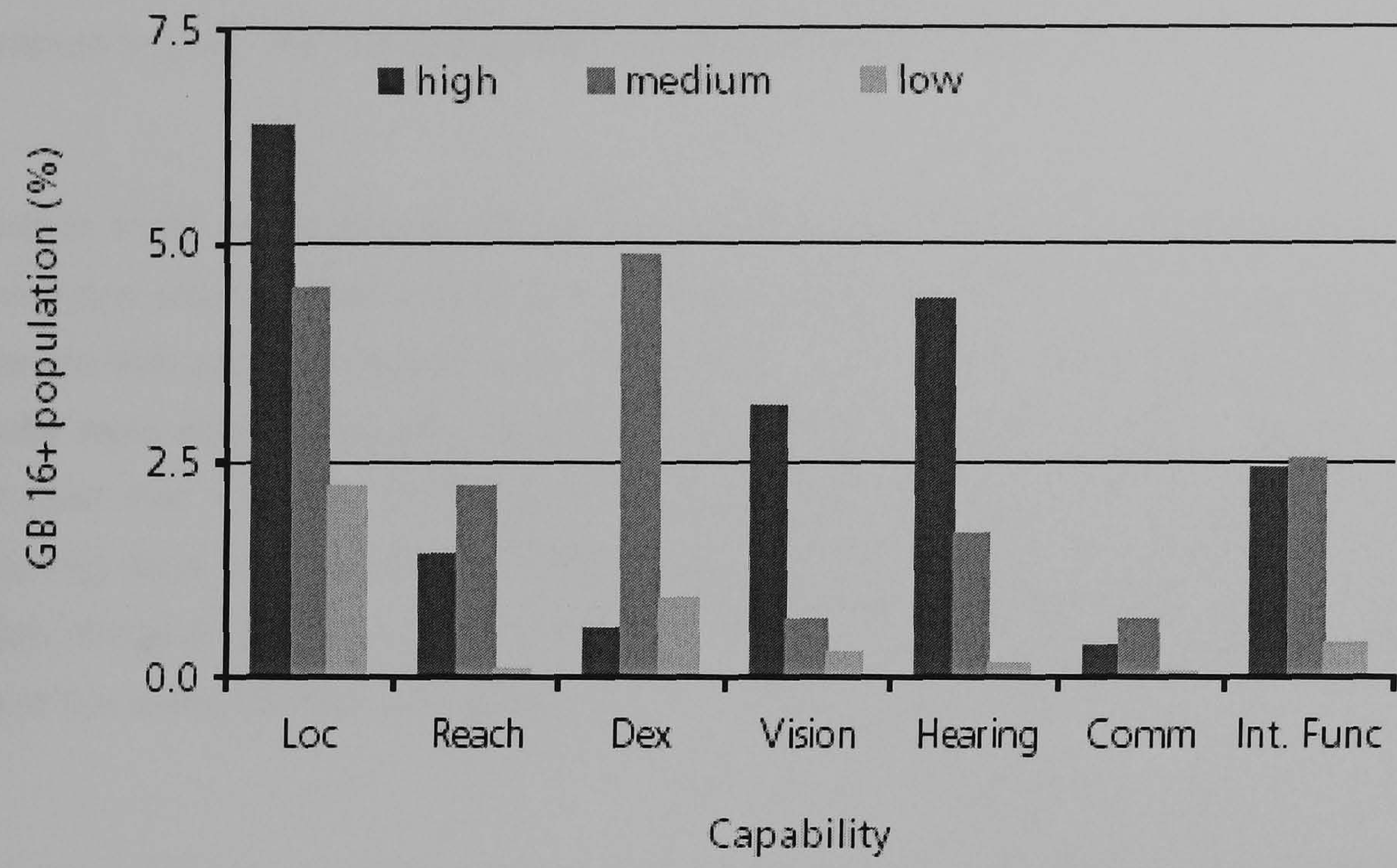


Figure 2.1 – Prevalence of capability losses in Great Britain for ages 16 to 49 (Clarkson and Keates, 2003)

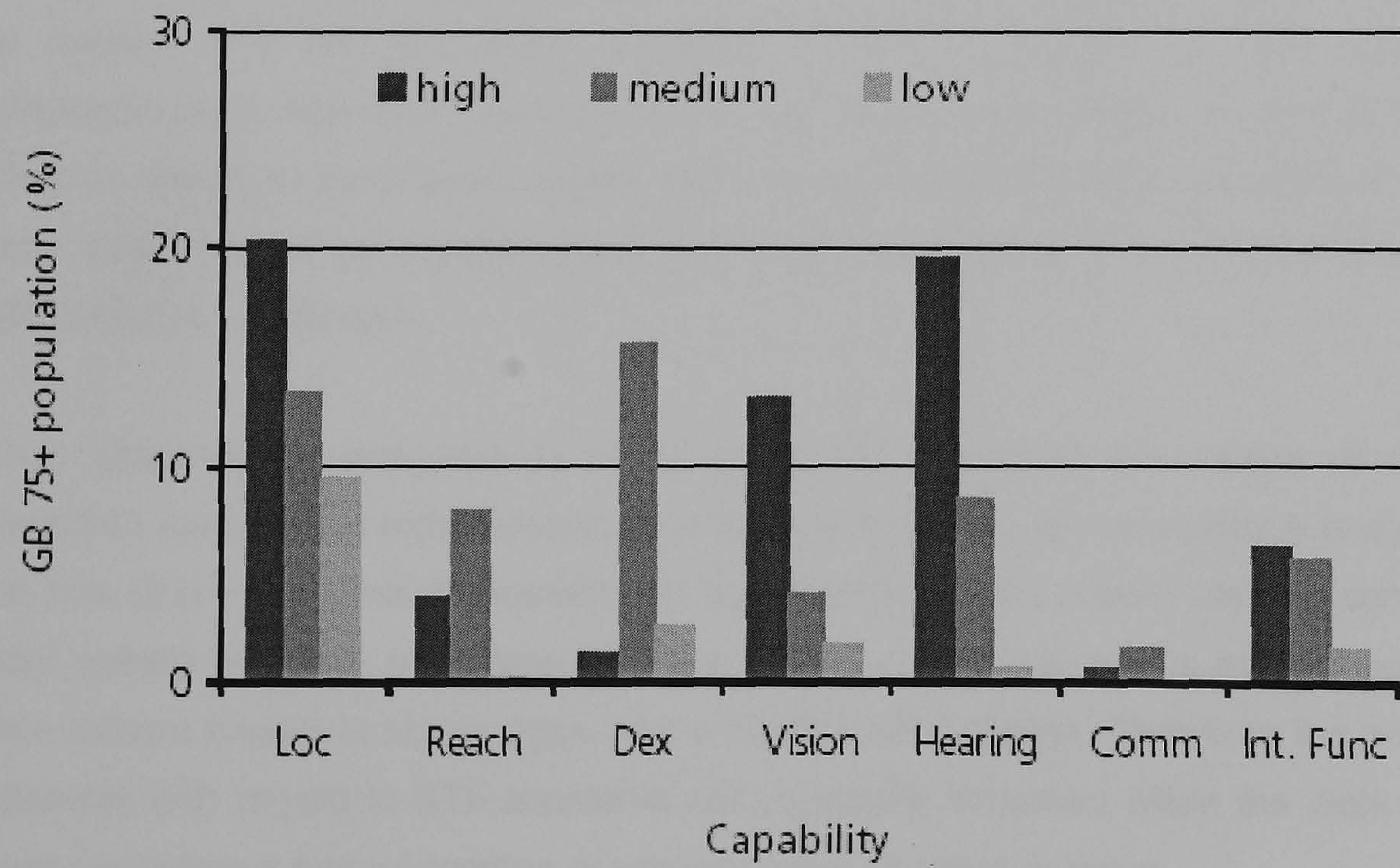


Figure 2.2 – Prevalence of capability losses in Great Britain for ages 75+ (Clarkson and Keates, 2003)

Roberts (1960) provides functional anthropometric data of elderly women and shows that due to the increased incidence of arthritis and other crippling diseases with age the joint movement range of the elderly is restricted. The physical fitness of the people deteriorates slowly but constantly up to the age of 70 and after that declines more rapidly. Physiologically, the result of changes to a person's body as it ages is that the systems and processes work less effectively in old age than in youth. Strength and dexterity in all kinds of physical activities can be reduced as a result of arthritic symptoms in the hands and feet (British Standards, 1999). The implications of these changes for the design of domestic environments are considerable and must be considered when designing work surfaces heights, the forces required to handle doors or window latches, etc..

Another study conducted by Voorbij and Steenbekkersb (2001), involving a total of 750 young and elderly, male and female subjects has shown that the percentage decrease in strength with age is similar for men and women. In the study, the differences between the sexes were mapped as well as changes in force capability with age. The relationships between five different isometric forces (pushing, pulling, twisting and left and right gripping) were also investigated. There was little decline in strength between 20 and 55 years of age and between 50 and 90 years of age, the percentage decrease in strength is about the same for men and women.

The Special Needs Research Unit (SNRU) of the University of Northumbria has conducted a study concerning elderly people's experiences with everyday products (Sandhu, 1993). The objective was to discover what design features make a product work and what features render a product inaccessible? Two of the selected appliances for the study were the cooker and the microwave because cooking is central to daily living and independence. It was found that ovens are too low for people who are frail or in wheel chairs or unable to bend and cookers with the controls at the back are difficult to reach and a safety hazard for anyone who is short or in a wheelchair or who has problems with sight, balance or seizures.

When designing a workplace to be used by the maximum percentage of the user population the fact that older people, both male and female, are more prone to slips, trips and falls (STF) accidents (Kemmlert and Lundholma , 2001) should also be considered. Older people fall more often than younger ones, and STF accidents might also have a more evident impact at higher ages where healing takes longer. Therefore the preventive measures with regard to STF accidents are especially important when the work force or users comprises a high proportion of workers aged 45 years or more.

In a study conducted with a group of Finnish elderly, it was found that the subjects had some difficulties with the top shelf of the upper cupboard (Kirvesoja et al, 2000). According to this study, which included a kitchen task, two-thirds of the subjects had problems reaching the top shelf of the cupboard of higher facilities. Based on that study a 1600 mm height for the top shelf of the upper cupboard was recommended as it suited almost all the elderly.

2.3.1.2 Multiple Capability Losses

Traditionally design research tends to focus on accommodating single major capability losses (Clarkson et al, 2003). This is because single major impairments are often the most noticeable and easiest to invoke the necessary motivation to address them. Then as there are no complex interactions with other impairments they are easily understood and comparatively easy to rectify.

However, as people get older they not only have one functional impairment but several. Consequently there is a need to make designers aware of the prevalence of not only one, but also multiple capability losses. Clarkson et al (2003) summarises the data extracted from the above mentioned disability follow-up survey to the family resources survey in the Figure 2.3.The 'motion' capability was derived from the combination of reach and stretch, locomotion, and dexterity; 'sensory' was derived from seeing and hearing; and 'cognitive' was derived from communication and intellectual functioning.

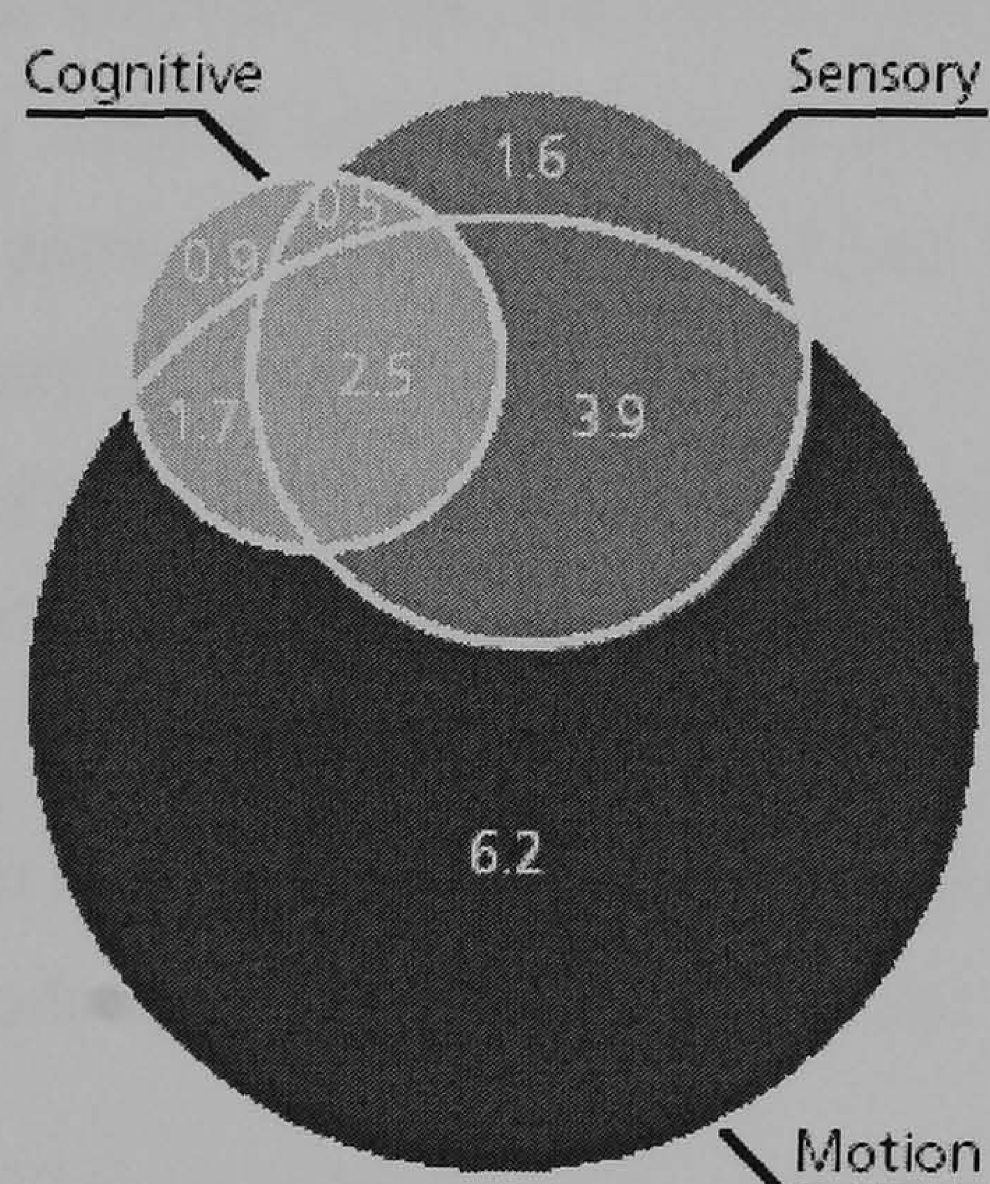


Figure 2.3 – The prevalence of multiple impairments for % of GB 65+ population (Clarkson et al, 2003)

2.3.2 Pleasure for the Whole Population from Inclusively Designed Products - Social Benefits

People use products mainly for their functionality or for pleasure. Increasingly people are demanding products that are both functional and pleasurable. This is the same for the older and disabled people. Jordan (1999) and Taylor et al (1999) describe four different types of benefits or 'pleasures' that products bring to their users. These are physio-pleasure which is concerned with the body and senses and they include touch, taste, smell, socio-pleasure which is the enjoyment gained from interacting with other people, psycho-pleasure which are the pleasures of the mind and ideo-pleasure which is the pleasure gained from things such as books, music and art.

2.3.3 Legislative Pressure

Various legislations enforced by many countries contribute to the legislative pressure applied on product developers. For most businesses, legislation and the prospect of expensive and public litigation arising from failing to meet the requirements of the legislation are the most persuasive form of motivation especially in the US. The main legislation in US is the Americans with Disabilities Act of 1990, Section 225 of the Telecommunications Act of 1996, and the new Section 508 of the Rehabilitation Act of 1973 (on Federal IT procurement) that came into effect June 21, 2001 (Ormerod and Casserley, 2003).

The 1995 UK Disability Discrimination Act (DDA) applies to any company that supplies goods and services to the public (Lebbon and Maclarty, 2003). Companies that do not consider older and disabled people will fail to develop products and services that are globally viable within this new context, and are likely to lose their share of local markets as customers are offered goods and services that better meet their individual requirements. The DDA is having a major impact upon service delivery and access to shops, public buildings as the successive aspects of the act are applied. Currently, there is no statutory obligation on companies selling products in the UK to design accessible products, although the Disability Rights Commission plans to seek a commitment from the Government to extend disability rights legislation (Underwood and Metz, 2003).

These legislations provide an important motivation to employ Inclusive Design approaches when designing products, workplaces, facilities or services.

2.3.4 Economic Benefits

Every commercial organisation likes to perform better than its competitors. In order to do this they either create a new market or increase its share of an existing market, thereby improving profit margins. Another method of extending the available market of a product is to increase of the proportion of the total market that product can address because of its characteristics through inclusive design (Underwood and Metz, 2003). In contrast this shows how much of the market is not available because the product lacks certain accessible features. A good example for the market gain by inclusive design is the Ford Focus car discussed later in this chapter. Underwood and Metz claim that due to the application of inclusive principles, the Ford Focus car has become the best selling car in the UK for the 32 months since its launch, and the best selling car in the world for the past two years.

2.4 Implementing Inclusive Design

As a first step in implementing the Inclusive Design approach products can be designed for a broader range of people. This means that when designing the designer should consider not only the people who use wheel chairs and who have visual impairment – which is usually the case in accessible design, they should also consider other factors such as strength and other disabilities. Maximizing the user population for a design can be achieved in two ways. Firstly, products can be designed to include as many users as possible by considering all of their characteristics. For example, a door handle can be designed for ease of use by considering a variety of different grips. Secondly, products can be designed so that they can be adaptable to suit different users with different abilities. For example, the walls surrounding a bathtub can be designed to support grab bars wherever they are needed (Steinfeld, 1994). In this way individuals can install grab bars in places that are best for them. The first approach requires designing special features from the start and the second approach allows for a range of adaptations depending on the individuals. The second approach will be less usable than the accessible design but the range of adaptability would be greater.

A number of different design strategies and approaches have been developed to achieve the Inclusive Design concept. The most prominent of them are described below. Although these approaches are called by different names and they employ different techniques, their ultimate goal is the same. That is to include all users in a product, workplace, service or a facility design.

2.4.1 Universal Design via Seven Principles

Universal design is an approach for developing products and environments so that people of all ages and abilities are able to use them to the greatest extent possible (Mueller, 2000). It has been developed in the USA over a period of 20 years or more. The intent of universal design is to simplify life for everyone by making products, communications and built environments that are usable by as many people as possible for no or little extra cost.

The Centre for Universal Design is a US national research, information, and technical assistance centre (www – Centre for Universal Design). The centre aims to promote the concept of 'universal design' in the built environment and related products by conducting research and assisting professionals who are working in this area. In 1997 the Centre proposed a set of seven principles that would enable the concept of universal design by guiding the design process, allowing the systematic evaluation of existing designs and by assisting to educate both designers and consumers.These seven principles as defined by the Centre for Universal Design are equitable use, flexibility in use, simple and intuitive use, perceptible information, tolerance for error, low physical effort, size and space for approach and use. These principles, although some of them can be just called 'ergonomic design' and do not specifically address the needs of disabled people, are used as universal design criteria in many universal design products and companies, especially in the US and Japan.

An example of the products the Centre has assisted in developing is the Ford Focus car shown in Figure 2.4 (Mueller, 2000). This car was designed with the aid of Ford's 'Third Age Suit'. The 'Third Age Suit' in Figure 2.5 is the result of a series of workshops based on an exercise developed in Canada and organized by Age Concern, a UK charity. This suit imposes on the wearer the reduction in sensory abilities, range of motion and strength that can occur with age. For example, while wearing this suit the wearer loses about 25% of their strength, and has 25% less flexibility/mobility resulting in it being harder to get in and out of a car.

Figure 2.4 – A picture showing the interior of Ford Focus (www –Focus, 2002)

Figure 2.5 – The Third Age Suit (Hitchcock and Taylor, 2003)

However, there are limitations in using the third age suit. For example older people exhibit a wide range of abilities and they use a variety of coping strategies when faced with a difficult situation. It is not possible, nor intended for the suit to predict these and further it should not be used to accurately quantify solutions to design problems (Hitchcock and Taylor, 2003). Furthermore, the suit is insufficiently developed to consider the complex synergies of restricted movement and to accommodate different states of degeneration or impairment.

Evaluation of these developed universal design products is also important in determining their success. Universal Design Evaluation (UDE) is a process of comparing the actual performance of these products environments and systems with their documented criteria for their expected performance (Wolfgang, 2000). When applied to UDE, it is possible to identify problems and develop solutions and also to learn about the impact on universal design on the users in general.

This approach stops people from being excluded from using products by arbitrary and ignorant design because different user capabilities were not considered during the design process. However, a question arises as to whether a single product or solution is available to address all the needs of the people due to the huge diversity of people and their capabilities. This fact has not been addressed thoroughly in this approach.

IDEA Centre

IDEA is the Centre for Inclusive Design and Environmental Access based at the University of Buffalo, New York (Centre for Inclusive Design, 2001). The centre claims that 'IDEA is dedicated to improving the design of environments and products by making them more usable, safer and appealing to people with a wide range of abilities, throughout their life spans.' The work of this centre includes the concept of universal design and provides resources and technical expertise in architecture and product design among other things. Some of the products they have assisted in developing are now commercially available.

Universal Design has become more of a philosophy rather than a systematic and practical design approach. There are very few structured descriptions of the implementation of Universal Design in the literature in more detail than broad design objectives. Therefore if universal design is to be implemented more research into the methodology for its implementation is required. UK and Europe are moving ahead on this area of research as described below.

2.4.2 User Pyramid Method

This method was developed in Sweden by an industrial design consultancy called Ergonomi Design Gruppen (EDG), which was established in 1969. Their designs start with the user and they try to make the product specifications to mirror exact user needs (Benktzon, 1993). To achieve this Benktzon proposes a method called the user pyramid method, which is illustrated by Clarkson et al (2000) as shown in Figure 2.6. In this method, mostly the physical aspects of the people, their vision and hearing are considered and not much attention is given to people with cognitive difficulties.

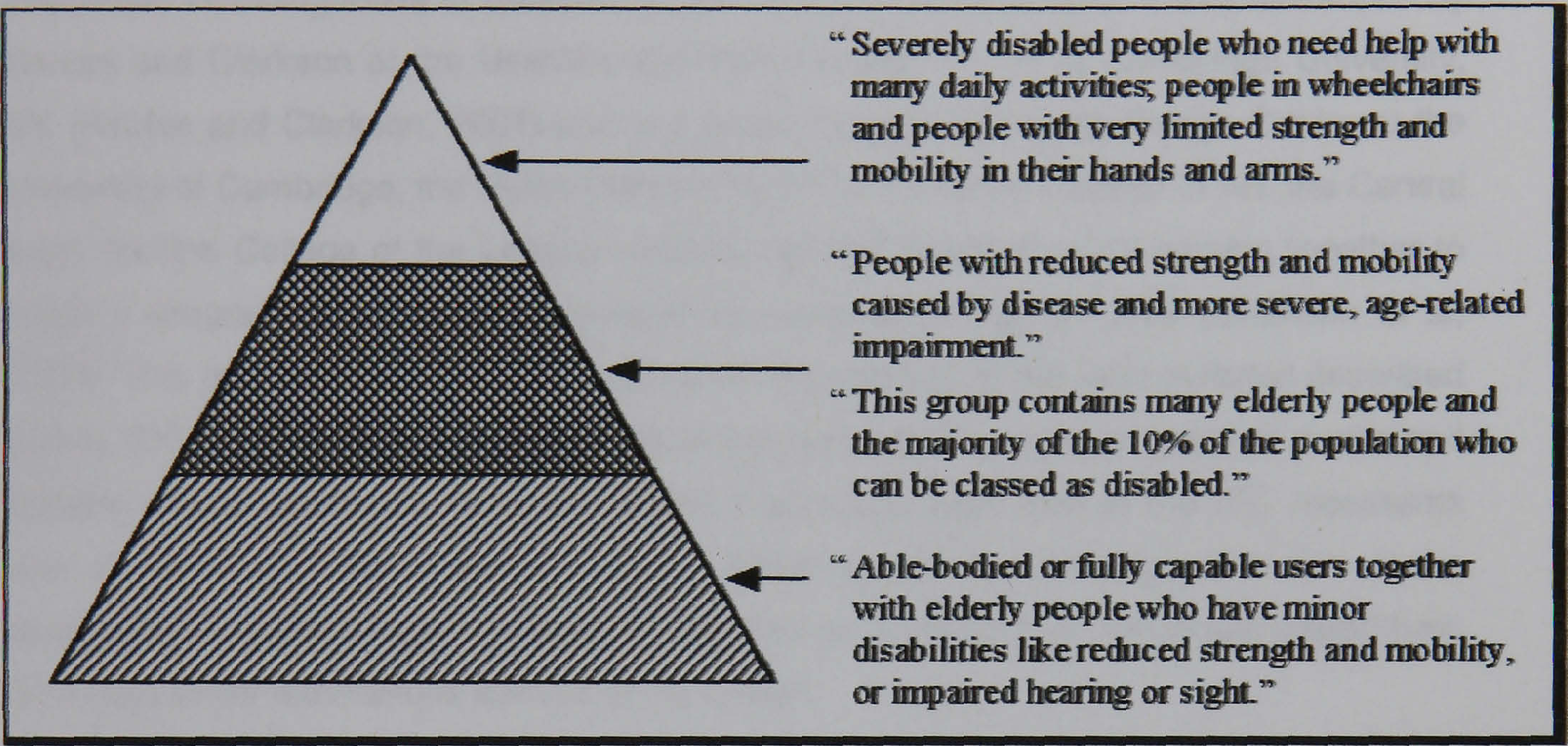


Figure 2.6 – The user pyramid (Clarkson et al, 2000)

The higher in the pyramid the demands on the products are specified, the more users it can accommodate. For example, the knife they have designed as shown in Figure 2.7 for people with arthritis can be used by everybody. It also improves functionality and according to Benktzon has established a larger market than the traditional adaptive aids market.

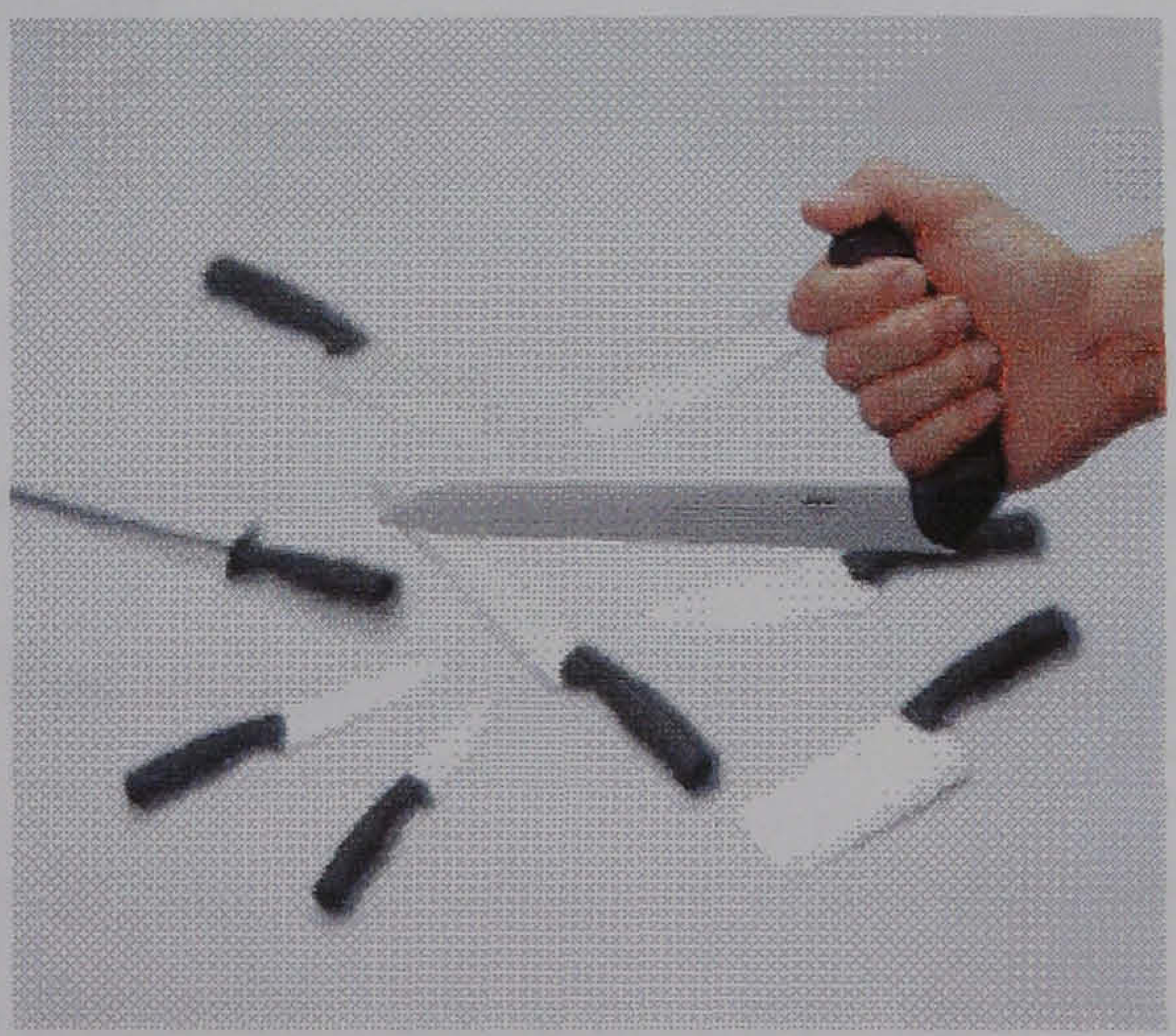


Figure 2.7 – A knife for use by people with arthritis (www – ErgonomiDesign, 2002)

EDG has studied many aspects of people with disabilities, especially the hand and arm capabilities. They have developed a large number of products that can be used by people with disabilities. Many of these products are modifications of existing products and the design and functionality of them make them attractive and easy to use by people of all abilities including the able-bodied.

2.4.3 Inclusive Design Cube (IDC)

The Inclusive Design cube encourages product developers to consider the wider population including those of disabled as well as able-bodied people. It was developed by Keates and Clarkson at the Usability and Rehabilitation Group at Cambridge University, UK (Keates and Clarkson, 2001) and is a result of the Engineering Design Centre at the University of Cambridge, the Helen Hamlyn Centre at the Royal College of Art, the Central Saint Martins College of the London Institute and the Design Council coming together to begin a programme of research focused on Inclusive Design in 1998 (Clarkson et al, 2000). This has been achieved by building on the concept of the user pyramid described above. IDC is a graphical representation of the user capacity level, population profile and suitable design approach. As shown in the Figure 2.8, each axis of the IDC represents user capability and the enclosed volumes reflect population coverage. The aim of the developers is to encourage designers to use IDC as a design tool, which can assist them to include users with various abilities in the design.

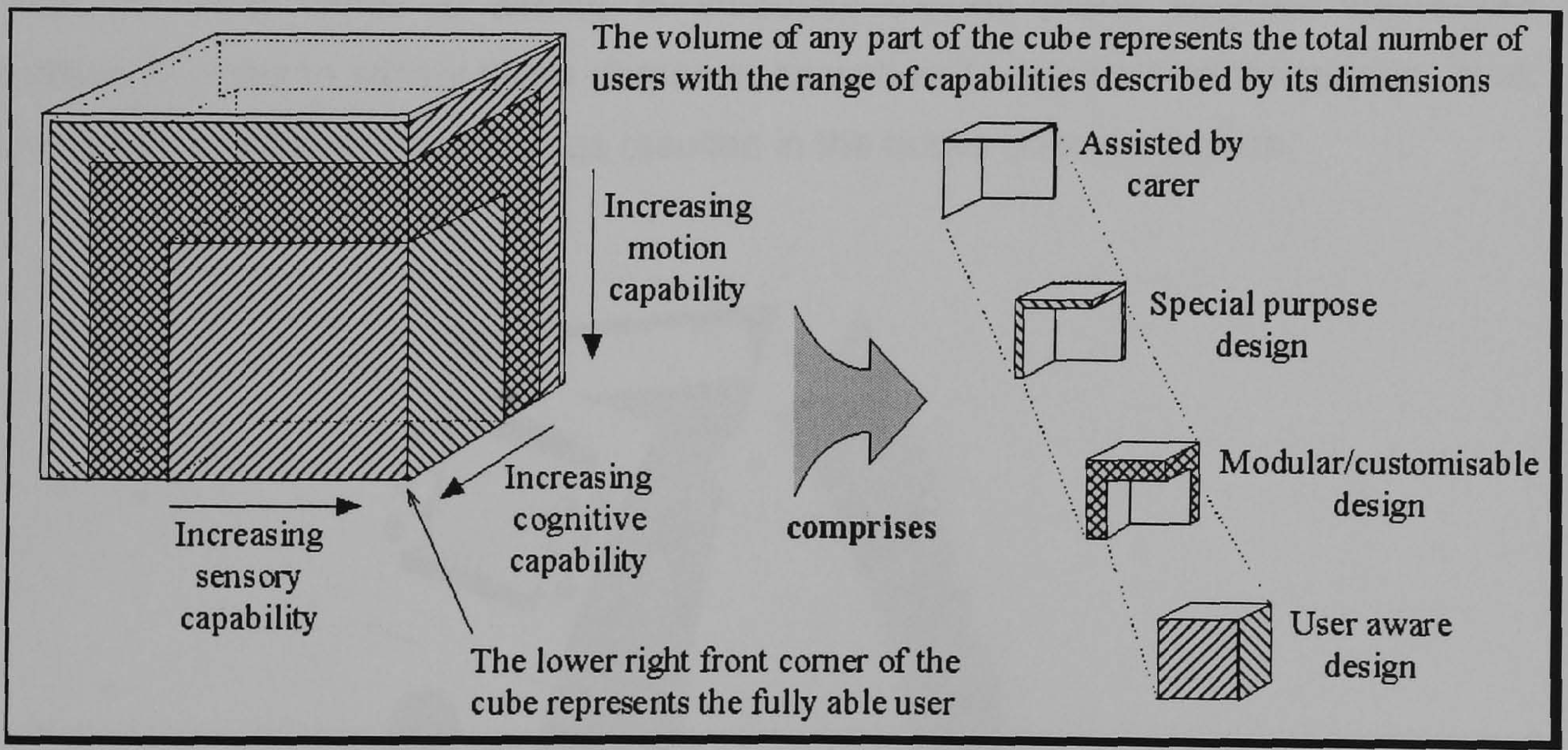


Figure 2.8 – The Inclusive Design Cube (Clarkson et al, 2000)

To comply with the universal design principles of producing products that are accessible to a wide portion of the population, the user aware design dominates the cube. The Inclusive Design cube leads the designers to different design approaches, which can be used to develop products, appropriate for a given range of capabilities.

In the right hand side of the Figure 2.8, the cube is shown populated by different design approaches. Each approach is suitable for a particular level of user capability and this approach contrasts with the universal design approach mentioned above by advocating different design approaches for different user capabilities instead of one design for all. Keates et al (2002) acknowledge the fact that the principles of universal design would produce products that are accessible to a large portion of the population and denote that approach as user-aware design, which is contained in the larger volume of the cube (Keates et al, 2002). However, they also note that the products designed by a user-aware design approach would be unlikely to be accessible to the less capable users and hence the need for other approaches given in the cube.

Another important factor of the IDC is that if the capability demands of a product are known and mapped back, a volume can be drawn in the cube to represent the population included. This can be used to assess design revisions to the product and then the inclusivity of the design variants can be compared visually. (Keates et al, 2002).

A product still under development using this approach is the concept Information point shown in Figure 2.9 . This is a case study by Cambridge University in conjunction with the Post Office (Keates and Clarkson, 2001). The age profile of the Post Office customers is biased towards over 65 because a large proportion of customers visit the Post Office to collect their pensions. The demands of the new automated customer Information Points (IP) that the Post Office is aiming to introduce include these people's decreased capabilities. In order to satisfy these demands as well as to ensure that the product is as usable and accessible as possible has resulted in the above concept system.

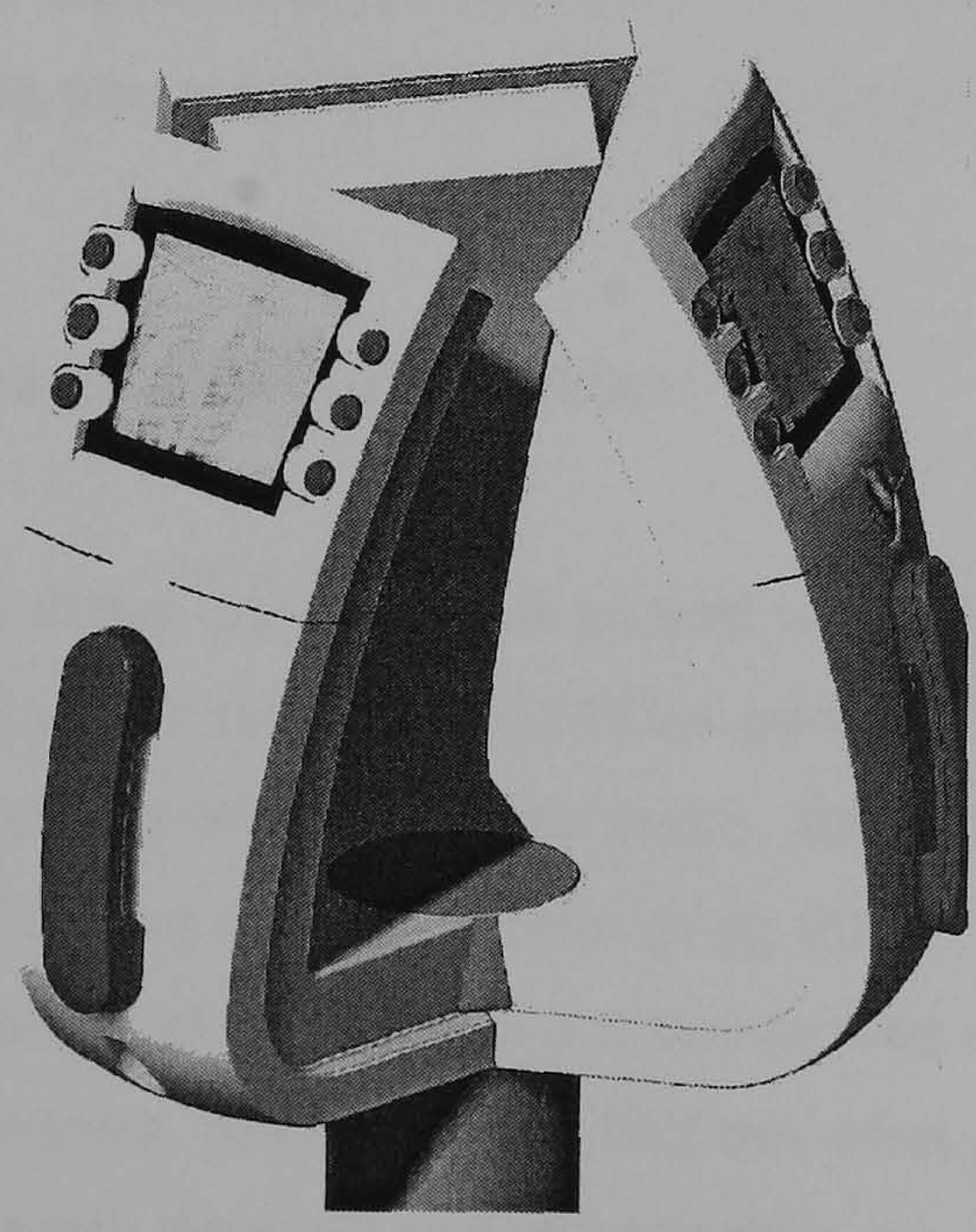


Figure 2.9 - The concept Information Point(Keates et al, 2001)

Keates and Clarkson (2001) have developed a design approach that uses the concept of the IDC called 'the 7 – level design approach' to aid designers in designing products to include as many people as possible from the user population.

The IDC and 7 level design approach can be used by the designers as design criteria and an evaluation process for the designed product and as a tool to determine the nature of the users accommodated by a design. However they do not provide the designer with specific tools for finding design parameters that increase user accommodation that can be used in the designing of products or workplaces.

2.4.4 'Design for All' Project

This project (Porter et al, 2002) was undertaken at Loughborough University, as one of a number of EQUAL projects. The EQUAL (Extending Quality Life) Programme was initiated by the UK Government's Office of Science & Technology in 1995 (www - EPSRC, 2001). EQUAL has initiated several projects, with the aim of drawing together research activities 'to extend the active period of peoples lives by helping individuals achieve a better life style, avoid or alleviate the effects of disability and participate more fully and actively'.

The 'Design for All' project is aimed at addressing the lack of data on anthropometry and capabilities to accurately represent disabled and older people in human modelling systems by building a multivariate database of individuals and by building a task based software tool to aid the Inclusive Design process. This project has two main elements; a user survey to collect data and a design tool to use this data in the analysis of designs.

2.4.4.1 User Surveys and Data Collection

One of the primary goals of the 'design for all' project was to build a multivariate database of real individuals including the disabled and older people. This database provides user data regarding the individual's anthropometry reach, strength and mobility in relation to activities of daily living (Case et al, 2000, Porter et al, 2002). In order to understand what the designers require in terms of people's data a survey was conducted among the design professions such as designers, engineers. To find out what the user needs are, another survey was conducted among disabled and older people.

The design professional survey showed that design teams do not often involve the user in the design process until the project is near completion or else they only include a few users who may not reflect the variety of different users (Gyi et al, 2000). Although most designers used at least one CAD/CAM package, they do not have data tools in a format or language that they can access and relate to easily. They preferred quick easily accessible data gathering methods due to the constraints to their time. Unless specifically requested by the client they do not attempt to include the needs of older and disabled users.

The user survey was based on a semi-structured questionnaire involving about 50 older and disabled people. This was followed by face to face and telephone interviews to gather data on different tasks based on factors such as reach, posture, grip, manipulation and viewability. The participants were 43 older and disabled people including younger disabled people, 5 people over 63 with no specific impairment and 10 older people with disabilities (Oliver et al, 2002 (a), Oliver et al, 2002 (b)).

The results of these interviews showed that most people wanted to maintain independence and perform the everyday activities that other people take for granted. Oliver reports that 42% of participants found it impossible to use their bath or needed considerable help, for example, another person and/or a hoist. In kitchen tasks more than 20% found that reaching high items and putting a dish into the oven was impossible while nearly 20% of the participants found that putting a pan on a back hob is impossible. Oliver et al report many coping strategies mentioned by the participants such as sliding heavy items along surfaces rather than lifting or moving heavy items in stages and sitting or kneeling on the floor for low tasks such as using the oven.

With the general household tasks, some participants reported that opening or closing windows only causes problems if they were high or too heavy and opening and closing doors caused problems if too narrow for a wheelchair. However, this survey has not gone into the details of the actual dimensions of the 'too high, too narrow' spaces. Many people interviewed needed help getting in and out of cars, and buses were inaccessible whilst lower buses were easier for ambulant participants. Cash machines were often at the wrong height. Based on the participants' specific needs, which for most of them was being able to function properly in the kitchen, the detailed data collection phase of the project involved lift-bend-reach activities concerned with cooking and using an oven.

The data collection involved 100 people, 75 of who were older and/ or physically disabled (Oliver et al, 2002 (a), Gyi et al, 2001). The data was collected using traditional methods and included external anthropometry, joint constraints and background information on severity of any disability and problems encountered with activities of daily living. It also involved capturing more novel data on link lengths, functional reach postural information and behaviours on a carefully selected set of task elements. All the data needed to recreate these individuals within a computer environment was collected with these participants. The database consists of multivariate data of individuals as opposed to population data.

The outcome of this project, HADRIAN is presented in the next chapter.

2.4.5 I~Design Project

This project was also launched under the EQUAL (Extending QUality Life) programme. This research is being carried out by the Helen Hamlyn Research Centre at the Royal College of Art, London (Lebbon and Coleman, 2003). The main objective of this project is to address the lack of information and guidance to the designers who attempt to design inclusively. Furthermore, five major tasks that are relevant to decision makers or to design managers and some to practicing professionals have been identified as necessary to advance inclusive design.

The biggest outcome of this project is the development of a toolkit for designers who are designing inclusively. Based on questionnaires, expert interviews and workshops that targeted design professionals, an interactive database from which useful material and references can be selected and organised on a job-by-job basis is being prepared (Lebbon, 2003). This tool is aimed at the design practitioners in a commercial environment of a design consultancy or a project team. This toolkit has an interface that allows information to be sorted and selected and output formats have that can be used to print off or used as part of presentations to clients or that can be used as reference material.

Lebbon claims that the toolkit will provide access to information that is directly relevant to inclusive design and also that it will introduce new-comers to the field, the reasons of why inclusive design has become an important aspect of design and development. Still in the development stage it will contain methods, case studies, a collection of images of users, links to agencies, companies, charities and other organisations. It will contain a listing of user research methods classified by activity type. The case studies will be related to the fields such as transport design, product design or communication design. These case studies will be backed by electronic versions of detailed published documents where available and web links will be available to relevant national and international organisations.

This toolkit is a giant step forward in educating and providing information regarding inclusive design to the design personnel. Although it does not provide a rigorous technique that can be used in the detailed design of products or workplaces it provides a method to find the information necessary to design for inclusivity, and information that leads to other sources.

2.4.6 Transgenerational Design

The need for transgenerational or multigenerational design arises from the consequences of the longer life spans resulting in an increasing opportunity for three or more generations to live together. A study of Singaporean society conducted by Parker (Parker, 2000) has shown that, in that multicultural society which has the most rapidly ageing population in Southeast Asia, there are a several generations living in the same dwelling. This is due to several factors including social benefits such as child minding or caring for the elderly or economical and environmental factors such as the demanding housing market etc.

Whatever the reason, several generations living together creates problems and demands on the environment that can only be solved by producing products, environments and services that can be used by all ages. Not only people of all ages living in a one house but also older people who use the same environment like, for example the street, shops etc. need things that are accessible to them as well as the younger people. An example of this is road signs, which need to be bigger and legible, for people with poor eyesight, a condition which most of the older people have.

Transgenerational design is designing for older people while at the same time satisfying the needs of the younger people (Woudhuysen, 1993). Woudhuysen addresses the functionality of the older and younger people. The younger people can sometimes be as functionally impaired as the old either temporarily such as by carrying too much baggage or permanently as visually impaired people.

From research conducted with elderly people in their houses, Freudenthal concludes that to design products that can be used across the generations, designers need data on the quantitative facts about the differences in physical, sensory and cognitive capacities. They also need insight into cognitive processes as far as is relevant to product use as well as more guidelines for the general market including the older customers and a broader theory about product use (Freudenthal, 1999).

However, this approach focuses only on the elderly population and not the capabilities of the people and does not provide techniques or tools that designers can use.

2.5 Trends in Inclusive Design

Research conducted by Moore (2003) in the US has shown that Universal Design, the counterpart of Inclusive Design in US is in danger of coming to a full circle in industry, despite on-going research. The Universal Design concept originated in the US as opposed to rehabilitation engineering and assistive technology in order not to segregate people and to include all. A survey conducted by Moore among US's leading industries has shown that many of them are again referring to 'accessible products' and some have no knowledge of 'universally designed products'. Even in the UK and Europe, although the interest of the Inclusive Design ideas have gained momentum in research circles, it is yet to find its way to the general market.

In this and the previous chapter, it has been established why it is important to design and produce products that include all the population. Although there have been some inclusively designed products in the market as shown by the above examples, the general public are still ignorant of this concept. The majority of designers although they are becoming aware of Inclusive Design, still do not use Inclusive Design concepts in their designs (Gyi et al, 2001). Hence it is crucial to understand in detail why the concept is still mainly in the research stage after almost 20 years of development.

The main factors that contribute to the Inclusive Design concept not becoming universal are identified from the literature. They are shown below.

- A lack of tools that the designers can access and use without further extensive training and without the cost of valuable time and money considering the fact that Inclusive Design involves a huge user population. To accommodate all these users, designers need to consider the ergonomics involved, anthropometrics etc. However, many designers are not trained ergonomists. Added to this, to analyse this huge database takes a lot of their valuable and expensive time.

  Therefore to popularise the Inclusive Design concept among designers it is necessary to provide them with proper tools they can use with ease. New design tools such as i~design at the Helen Hamlyn Research Centre, RCA (Lebbon, 2003), which is a tool that enables designers and senior decision-makers to apply inclusive design and its strategies, inclusive design cube (Keates et al, 2002) which provides a design tool to enable complete population coverage and

HADRIAN (Marshall et al, 2002) which enables a CAD model of a product to be usability tested using a database of individual people's abilities and disabilities. These tools however do not provide technical assistance to designers in the detailed design process and with respect to the abilities of the user population.

From these tools HADRIAN provides a both a database of users and a task analysis tool that can be used to evaluate detailed design models. Even this does not provide facilities to increase the user accommodation. However, HADRIAN provides a very good starting point to create a new approach.

- A lack of a proper method for designers to follow when designing for the whole population – although the Centre for Universal Design has specified some guidelines, they just provide an overall idea for designs and do not provide much help for the detailed design process. Research is being carried out in this area at Cambridge University (Keates and Clarkson, 2001) and the Helen Hamlyn Research Centre at the Royal College of Art.
- A lack of consumer and manufacturer education – although many an effort has been made to research these concepts there has been relatively less effort made to educate consumers and manufacturers of products. This is important because although people, especially the older people feel that they cannot use products they tend to assume that the fault lies with their incapability and not with the product. People must be educated so that they know it is not only possible to manufacture products that can be used by all but also that these products have already started to come into the market. This will generate consumer pressure on the manufacturers to design for inclusivity. The author believes that this can be achieved best by educating the undergraduates in the engineering and marketing areas.
- A need for these Inclusive Design approaches to move forward from theorising to the practicalities of design.

The research carried out on Inclusive Design by various researchers has achieved a great deal in identifying the needs and characteristics of the user population and specifying guidelines and design approaches. This work has shown that great variability exists between users and to accommodate them all designers must consider all of their characteristics and capabilities as well as the aspects of the product designed. Especially the work done in the 'design for all' project has shed a new light onto the way designers use users' physical dimensions and capabilities.

2.6 Users as Individuals

The 'Design for All' project group has shown that in contrast to the traditional way of using population data, data regarding each individual should be used in the design of products, especially when Inclusive Design is considered (Porter et al, 2002). Typically, designers use percentile values of population data in their designs. These population data can be explained in the following way.

For a homogeneous or closely defined population, anthropometric data follows a reasonably normal (Gaussian) distribution as shown in Figure 2.10. In those cases, the data cluster in the centre of the set at the 50th percentile coincides with the mean (the average). The peakedness or flatness of the data cluster is measured by the standard deviation. Depending on the population the distribution can be normal, skewed, bimodal or any other form and the percentiles of the data set can be found either by using a graph of the distribution and finding the percentile values from the graph or by calculating them using well-known mathematical formulae.

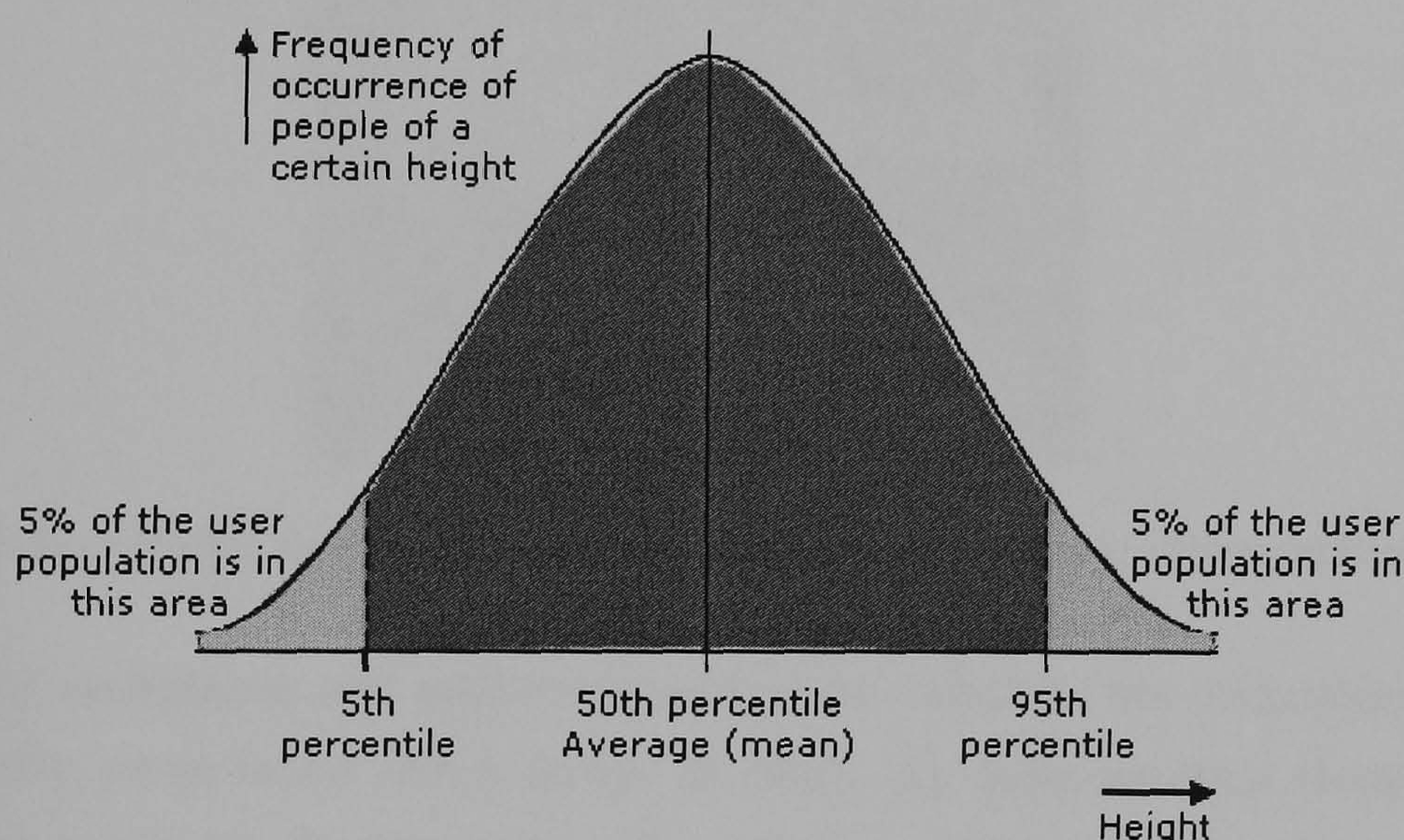


Figure 2.10 – A frequency distribution histogram of heights of a population

There are various methods of gathering population data and also many databases exist that provide these.

2.6.1 Anthropometric Data for Populations

Anthropometry is the branch of human sciences that deals with body measurements such as body size, shape, strength and working capacity (Pheasant, 1996). Anthropometrics are used to describe the "user" or "target" population for a product. As described in the introduction in this thesis, the study of anthropometrics dates back centuries. Earlier ideas of artistic human proportions have evolved into sound scientific and engineering practices. The Belgian statistician Adolphe Quetelet was the first person to apply statistics to anthropological data, thus beginning the modern anthropometry in the middle of the 19th century (Kroemer et al, 2001).

There are two types of anthropometric measurement, namely static and dynamic anthropometry. Static anthropometry deals with measurements of humans in standardised static positions as shown in Figure 2.11 while dynamic anthropometry deals with measurements of humans at work or in motion (Hertzberg, 1960) and usually implies the study of the workspace and the space envelope needed by people as they perform work.

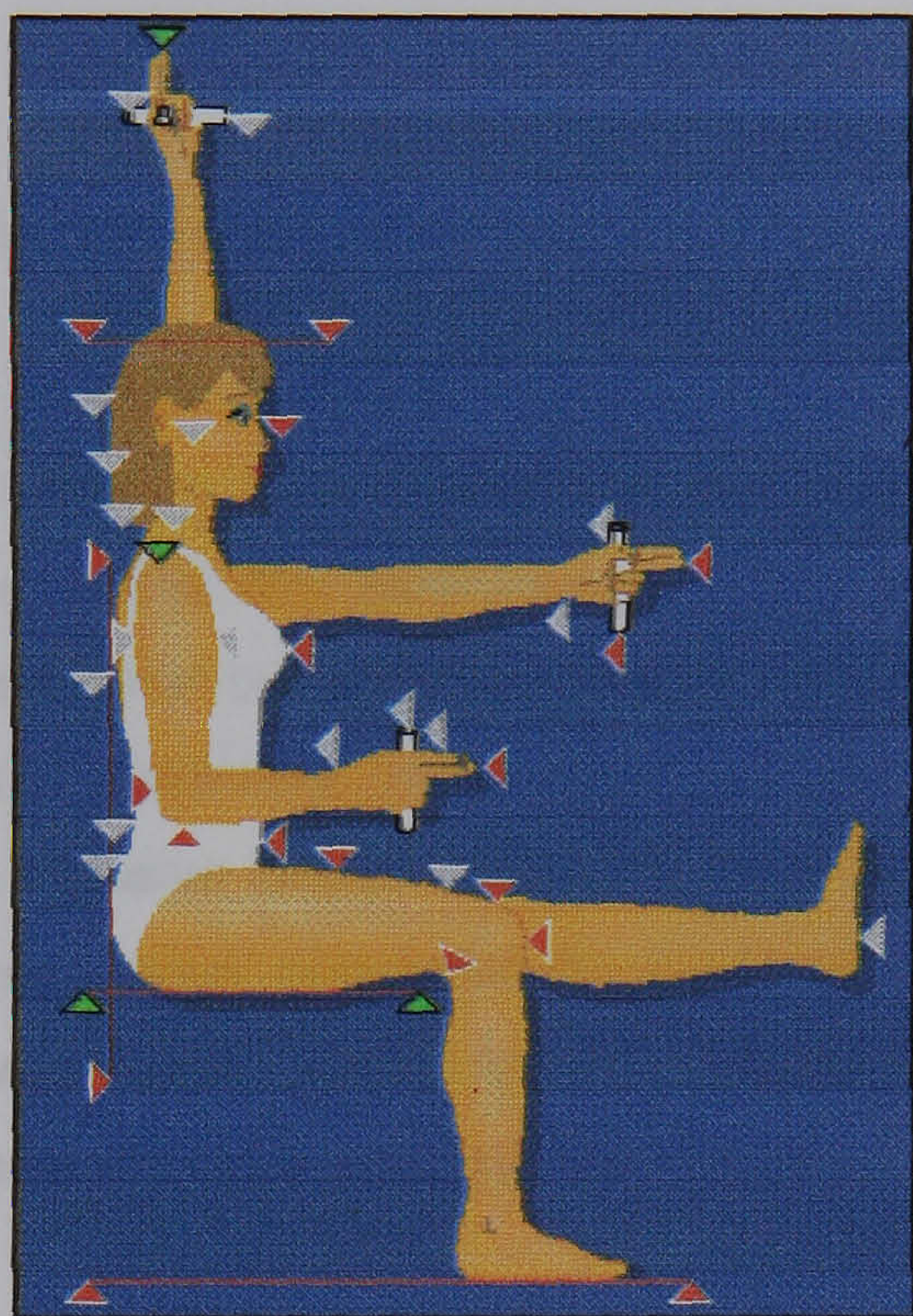


Figure 2.11 – Static Anthropometric Measurements (www - PeopleSize 2000)

The design of workplaces and products needs to be based on the anthropometry of the users. Typically, when faced with a design problem, the designer must study and get to know exactly whom the design is for. This must be done with careful consideration because of the differences of the anthropometric data between groups of people. Anthropometry differs between different nationalities, gender, age, occupation, and ability e.g. wheelchair users. There are also differences between designing for a specific group and the general population, because the anthropometric characteristics of any population are dependent upon a large number of biological, social and demographic variables (Boussena and Davies, 1987, Bolstad et al, 2001).

For example, in comparison the body sizes of elderly women were smaller than the younger female population in Britain (Roberts, 1960), stature for instance, being some 75 – 100 mm below that regarded as average for British women. This may be due to the possibility of tissue shrinkage as well as postural factors, for in many the stoop of age is firmly established, causing a reduction of all vertical measurements in which trunk height is involved. Damon and Stoudt also reported similar findings (Damon and Stoudt, 1963) among Spanish - American war veterans.

After determining the user population, the anthropometric data is obtained by measuring a set of subjects that are representative of the total user population or if the required data has been collected earlier by someone else, by referring to those available data. Nowadays there is an abundance of anthropometric data about able-bodied people especially in western countries.

2.6.2 Need to Consider Individuals in Inclusive Designs

The data obtained from the above-mentioned anthropometric databases are used in typical human modelling systems. It is relatively simple to use physical dimensions and joint constraints such as extent of arm extension, in a human modelling system, but it is more difficult to incorporate other capabilities such as those described in section 2.3.1.1 and 2.3.1.2, due to their high variability. These different capabilities, which designers must take into account for the Inclusive Design approach, vary hugely from each other to the extent that finding a 'homogeneous' population for the traditional representation of human data becomes almost impossible. Reasons why population data do not meet the requirements of the inclusive designer are described below.

2.6.2.1 A Statistical Point of View

The problem of using these statistical population data of people in designing is that people's body sizes vary from individual to individual and even in one individual there is no relationship between various body parts (Hertzberg, 1960). For example, a short person can have long limbs or vice versa. This was shown clearly by Hertzberg when a study made to test the assumptions of the 'average man' by Daniels and Churchill were published. Figure 2.12 shows a summary of these results. Interestingly, this study was made on a highly homogeneous population of more than 4000 flying personnel to see how many men could be average in 10 dimensions. On top of this homogeneous population they have also accommodated plus and minus 15% from the average in their figure, which was called 'approximate averages'.

The below figure shows that if only one dimension, e.g. stature was considered there are 25.9% of average people and that if for example four dimensions such as stature, chest circumference, sleeve length and crotch height were considered the percentage drops to only 1.8%.

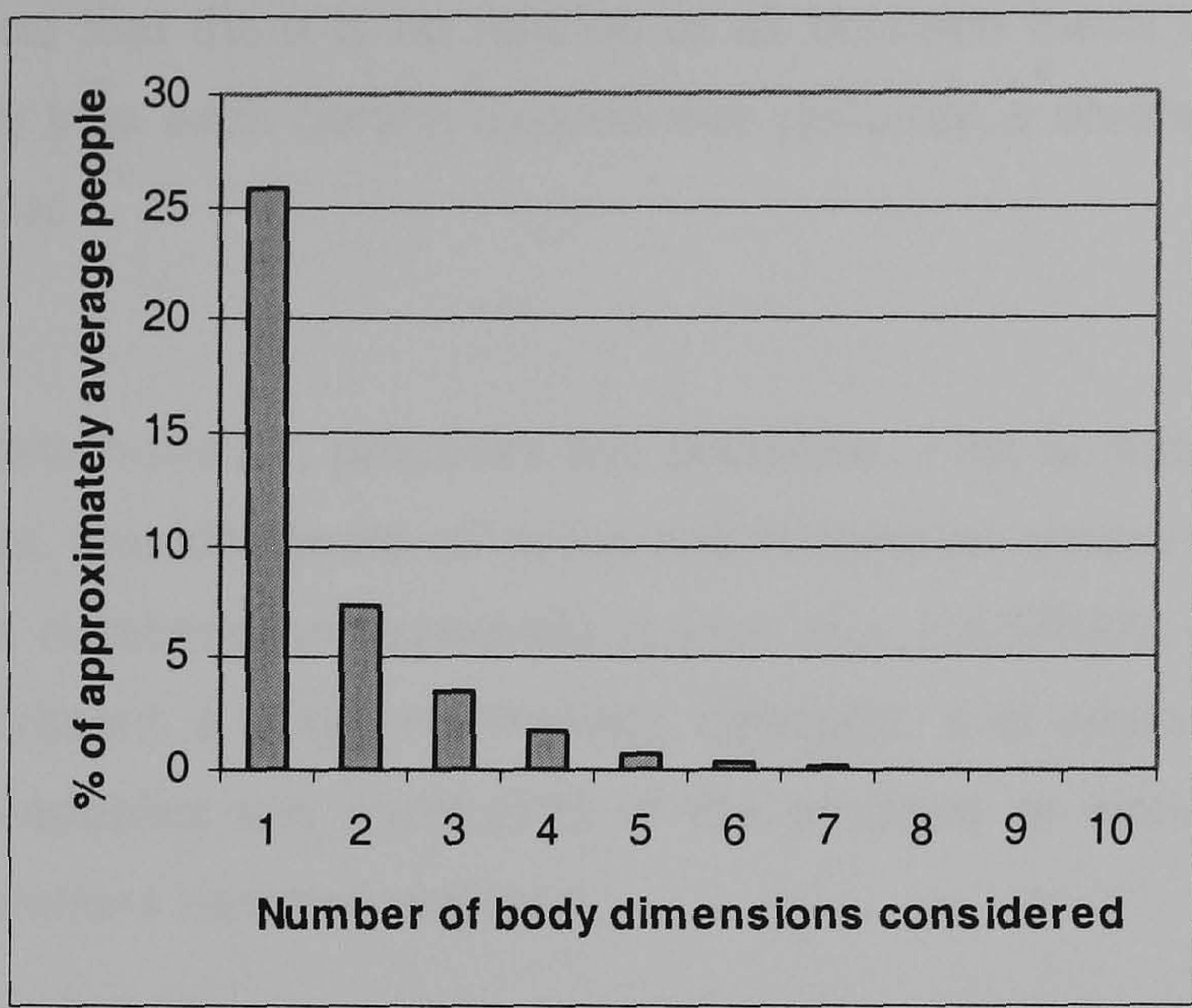


Figure 2.12 – Percentage of average people against number of body dimensions

Figure 2.13 shows the poor correlation of dimensions within an individual as obtained from USAF flying personnel (Porter et al, 1993). In that figure A to L represent the stature, sitting height, buttock-knee, shoulder breadth, hip breadth (sit), arm reach (functional), weight, knee height (sitting), elbow height, forearm-hand, biacromial diameter and eye height respectively.

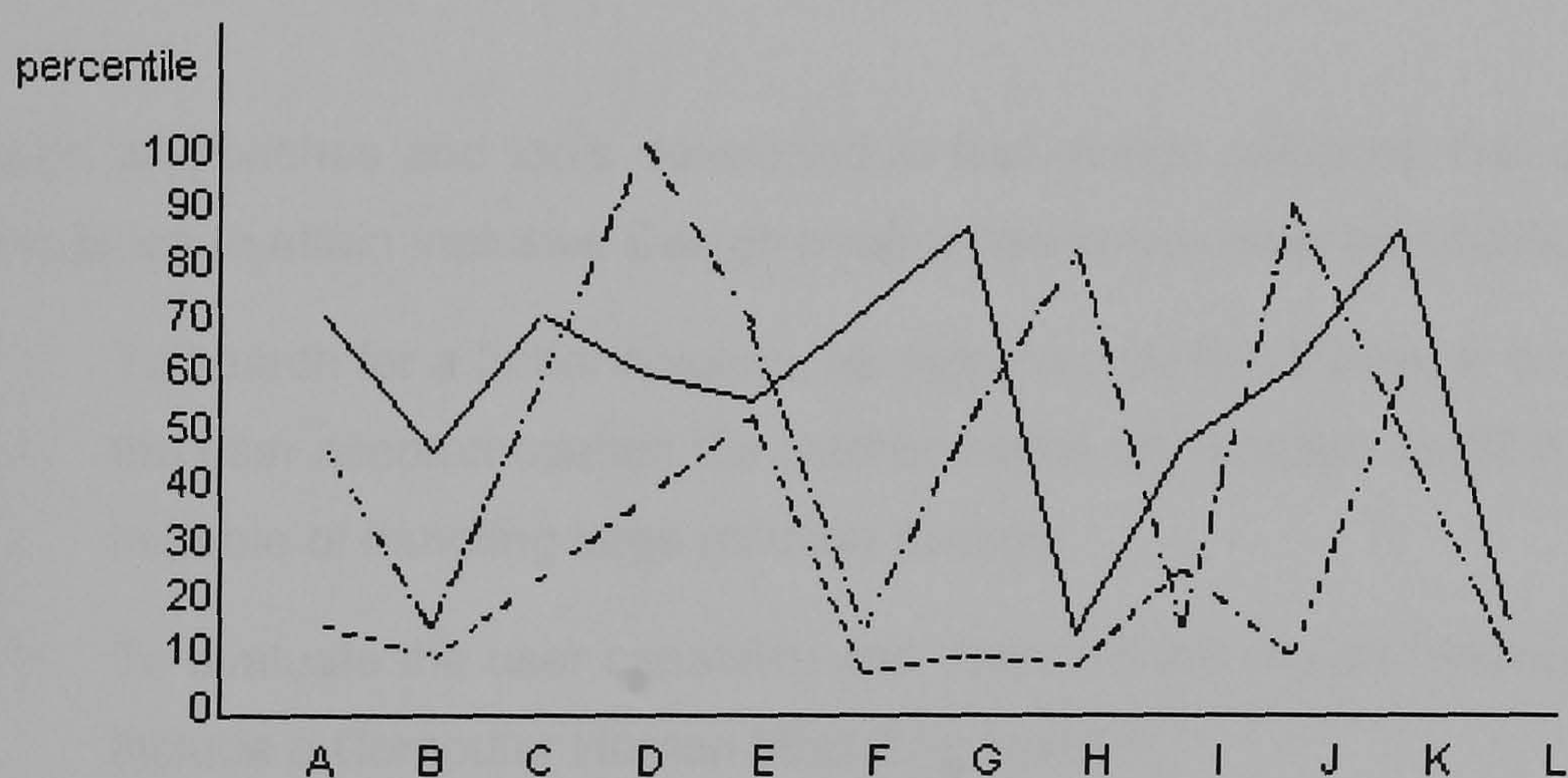


Figure 2.13 – Poor Correlation between body measurements of people

These poor correlations between individual's body measurements pave the way for a new approach in anthropometry. Namely, that of presentation of anthropometric data of individual people. When considering disabled people and various kinds of disability, this correlation becomes even poorer and the designer's necessity to know the needs of the individual increases.

Another case against the use of population data is the difficulty in finding a closely defined homogeneous population in modern cosmopolitan society. These facts reinforce the concept of using individual data. The fact that the older people may have multiple capability losses and that there is no relation at all between these capabilities and the degree of capability loss each person experiences generate a diverse set of individuals with variety of abilities.

Use of individual data however, produces two problems. First is finding these individual data regarding users. The 'design for all' group has initiated an answer to this by gathering and incorporating a database on individuals in their tool, HADRIAN. Secondly, all these individual data represent a huge multivariate database and when considering these together with the variables and constraints of the products or workplaces, the search space for design solutions becomes colossal.

Therefore any attempt to search for better solutions for the design of products or workplaces in order to maximise user accommodation that uses individuals' data has to consider methods of tackling these huge search spaces as well as methods of ergonomically evaluating the users and their capabilities with regard to the design. Designers must have tools to consider all this and achieve inclusivity in designs with minimum effort and time for Inclusive Design concepts to achieve the popularity they deserve.

The design approaches and tools developed to find design solutions that maximise user accommodation to attain Inclusive Design must possess two main capabilities.

1. To search for a better solution, as proposed by this thesis, in order to optimise the user accommodation the mathematical optimisation method used must be capable of handling large solution spaces.
2. To evaluate the user capability and user and the design interaction they must include a Computer Human Modelling system.

2.7 Mathematical Methods to Tackle Multivariate Data for Optimisation

Mathematical optimisation is the formal title given to the branch of computational science that seeks to answer the question `What is best?' for problems in which the quality of any answer can be expressed as a numerical value. In order to tackle the multivariate data mentioned in the above section and to search for better solutions, a mathematical optimisation method capable of handling a large amount of data is essential. Although many optimisation algorithms are available, many methods are appropriate only for certain types of problems. Thus, it is important to be able to recognise the characteristics of a problem in order to identify an appropriate solution technique.

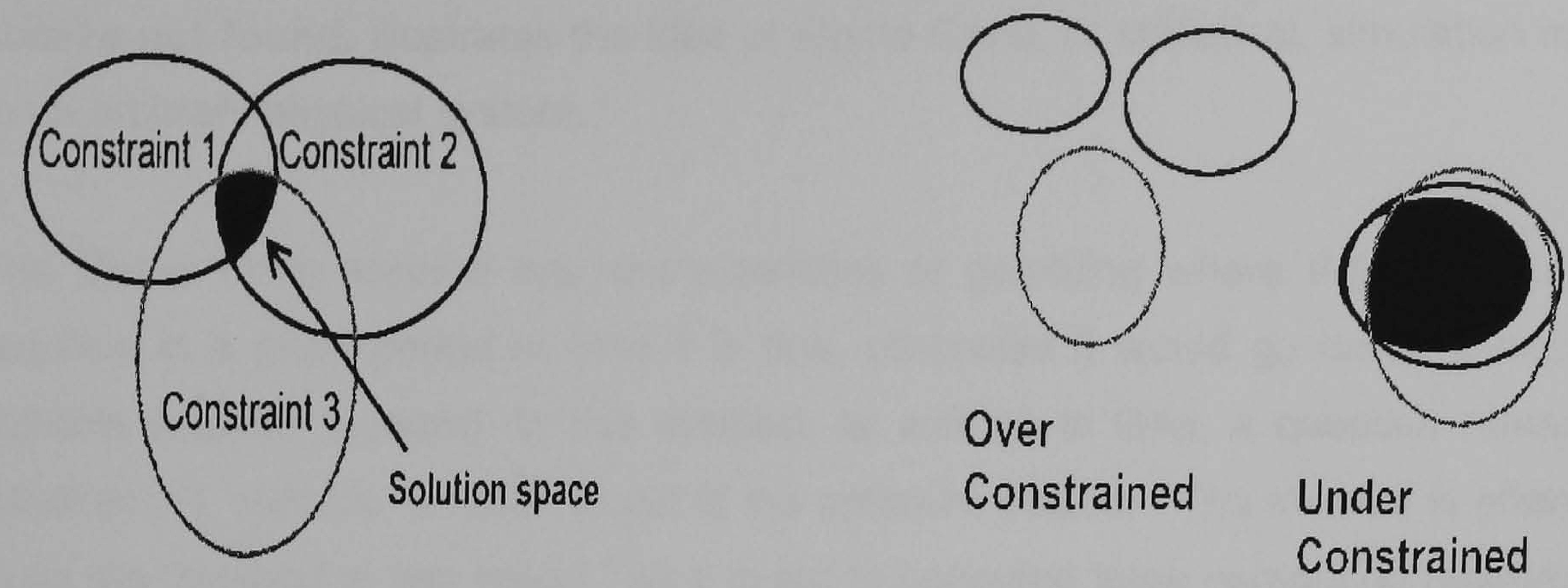
There are many tried and tested mathematical methods to handle this problem and the beauty of it is that they can be used within a computer system in the same way as most mathematical methods. Some of these methods that have the potential for use in the above problem are described below.

2.7.1 Constraint Modelling

This is an optimisation technique that can be used to analyse multivariate data and to find a solution within given constraints. Another capability of the constraint modelling approach is to give the designer a tool that could help identify the genuine requirements of a system, be they functional, geometric, manufacturing or cost requirements and by using these, determine the values of design variables.

Putting it in the simplest form, constraint modelling defines a possible design solution or solutions within a set of constraints. This may be the most convenient method available in more general design situations where a designer meets a design task for the first time. In situations like that even when the precise rules, which govern the design, are not obvious, constraints that bound what can be done are often clear (Mullinuex, 2001). With regard to sketching systems where constraint modelling has been used extensively the interest is in trying to interpret a designer's intention from what is essentially a free-hand sketch performed with the CAD environment (Latham and Middleditch, 1996). There it is necessary to determine the constraints such as perpendicularity and parallelism that specify the geometry. Once the constraints and an objective function that specify what need to done e.g. minimisation of cost, have been established a mathematical optimisation technique is used to search for the best solution within the constraints.

As illustrated on Figure 2.14(a), a feasible design is a design that satisfies all the constraints. If the design is subject to too many constraints, a solution may not exist that satisfies all the constraints. On the other hand, if the constraints are too general, there will be too many solutions to the problem and a true optimum solution will not be found (Figure 2.14 (b)). The task of the designer is then to determine which constraints are to be relaxed and where to introduce more constraints (Whitward, 1995).



(a) A feasible solution within constraints (b) Over and under constrained

Figure 2.14 - Use of Constraints

2.7.2 Genetic Algorithms

Another optimisation technique that can be used in multivariate analysis is Genetic Algorithms (GA), which constitutes a high-level decision support technique during the preliminary stages of the design process and a powerful tool for the detailed design of complex components (Bullock et al, 1995). It is a non-linear search and optimisation technique and is well suited to the solution of multivariate design problems. The general structure of the algorithm is considered to be broadly analogous to the process of Darwinian evolution in that genes pass good characteristics from generation to generation.

A key feature of GAs is that the search is conducted from a number of points rather than a single point thus increasing the exploratory capacity (Balakrishnan and Jacob, 1996). There are many applications for GAs such as assisting the design engineer to work more efficiently by automating some of the selection and sizing tasks required (Crossley and Laananen, 1997), and GA's have been used in the creation of aesthetically pleasing designs (Case et al, 2002).

2.7.3 Monte Carlo Method

Another technique to find solutions for multivariate problems can be found in the Monte Carlo method, which involves selecting a solution for a problem at random and checking whether it satisfies all the conditions (Chandler et al, 1968). Unsatisfactory solutions are discarded and another one is selected at random. Monte Carlo methods have been used for centuries, but only in the past several decades has the technique gained the status of a full-fledged numerical method capable of addressing the most complex applications. Monte Carlo is now used routinely in many diverse fields, from the simulation of complex physical phenomena such as radiation transport in the earth's atmosphere, to the mundane, such as the simulation of a Bingo game (Eckhard, 1987). **Error! Reference source not found.** illustrates the idea of Monte Carlo, or statistical, simulation as applied to an arbitrary physical system.

The Monte Carlo Method has characteristics of gambling where the correct answer is reached in a short period of time it is fine, otherwise it would go on indefinitely until a suitable solution is found. In this method, as well as in GAs, a question remains as to whether the 'suitable' solution found is the optimum solution. The method is often referred to as the "method of last resort," as it is apt to consume large computing resources some applications needing very large computer facilities (Eckhard, 1987).

2.7.4 Simulated Annealing

There are other algorithms that can be used to find solutions for multivariate problems such as Simulated Annealing (SA). SA exploits an analogy between the way in which a metal cools and freezes into a minimum energy crystalline structure (the annealing process) and the search for a minimum in a more general system (Metropolis et al, 1958). The algorithm that has been developed by Metropolis et al was later used in optimisation problems. In these problems the relationship between physical annealing and simulated annealing was described as shown in the Table 2.1, which was taken from Dowsland (1995).

Table 2.1 - Relationship between physical annealing and simulated annealing

Thermodynamic Simulation	Combinatorial Optimisation
System States	Feasible Solutions
Energy	Cost
Change of State	Neighbouring Solutions
Temperature	Control Parameter
Frozen State	Heuristic Solution

There is some difficulty in using this method due to the handling of constraints when using the SA algorithm. These constraints are defined to the system together with the cost function. In many cases the routine can simply be programmed to reject any proposed changes, which result in constraint violation, so that a search of feasible space only is executed. However, there are two important circumstances in which this approach cannot be followed:

- If there are any equality constraints defined in the system, or
- If the feasible space defined by the constraints is (suspected to be) disjoint, so that it is not possible to move between all feasible solutions without passing through infeasible space.

Since one or both of the above conditions occur in Inclusive Design situations this method was not considered for the research.

All the methods described above are able to accommodate a large amount of data to find solutions to multivariate problems. Many of them use some random search methods. A limitation of GAs is that while the models used for preliminary design are often relatively simple, those used for detailed design are generally computationally expensive. Also the efficiency of a GA search can be significantly reduced in heavily constrained design spaces whereas in constraint modelling any number of constraints can be specified without forfeiting the efficiency and with only a little reduction in speed. Mullineux (2001) points out that although GAs or simulated annealing approach find all possible solutions, they only work well in finding a general area of a solution but not in finding it to any great accuracy. On the other hand the solution found in constraint modelling is bound to be within the constraints specified and hence is a suitable solution.

All these factors and the availability of the software SWORDS has made the decision to choose constraint modelling as the mathematical method for the new approach.

2.8 Computer based Human Modelling Systems

The traditional design of working environments is intended mainly to ensure that 'work' can be performed effectively (Kuusisto and Mattila, 1990). 'Human factors' have been considered to be less important. In the early days, Human-factors (HF) engineers typically had to interpret anthropometric tables themselves. Using the information given in anthropometric tables - which consist of measurements of standard anthropometric variables derived from representative samples of human populations, HF engineers would draw reach and visual envelopes or even construct 2D cardboard manikins to replicate the seated, standing and crawling movements of product users.

Computer models of humans are recent technology innovations for evaluation of human-machine-environment interactions. They are more complex than drafting manikins, more like electronic counterparts of the physical manikins described above. These manikins used in CAD systems provide complex data handling facilities, which enable designers to access human factors databases at the point of use (Brennan and Fallon, 1990). They assist designers in visualizing their creations and they provide facilities for simulation, both graphic and dynamic as well as providing means to quantify human inputs in the systems design.

Basically, human modelling and simulation is a mathematical representation of human characteristics or behaviours (Kruithof and Ziolek, 2000).

Usually, only the physical attributes of humans such as shape and size are modelled. There are two kinds of digital humans. The first kind are manikins used for illustration which are an 'ideal' representation of the human form but have limited functional value for analysis and evaluations. The second are those used for analysis and development. The simulation of human motion is another aspect that can be used in design evaluation. This has been achieved in some researches by the use of biomechanics and artificial neural network systems (Wright et al, 2001, Taha et at, 1996).

There are various advantages in using human manikins for evaluation of designs rather than using real humans in built environments. First, it allows the designer or the ergonomist to save a lot of money and time by addressing the user centred design issues early in the development cycle by using 'virtual mock-ups', where changes can be made easily and quickly. Secondly, using virtual human models allows control over the test subjects' characteristics such as size and shape, whereas in real life it is difficult to find ideal subjects.

Another advantage is that most digital ergonomics software packages allow designers to 'see' what the manikin sees. Then the virtual human allows the user to test potentially dangerous conditions. It is often easier and safer to use these manikins instead of older and disabled people in user trials hence making it an ideal tool in Inclusive Design approaches. However, to succeed in developing a user friendly design, users of these systems typically need to learn biomechanics and anthropometry as well.

CAD systems also have the ability to demonstrate the user machine compatibility and to evaluate quantitatively human performance in a proposed design. They could be used to demonstrate the consequences of omitting human engineering inputs in the system design process. There are many CAD systems available nowadays and some also contain a human model to evaluate the ergonomics aspects of the users. A few of them are described below.

2.8.1 SAMMIE

SAMMIE - **S**ystem for **A**iding **M**an-**M**achine **I**nteraction **E**valuation (Porter et al, 1999) originated in the late 1960's and has been used as a consultancy tool since 1978. SAMMIE provides a three dimensional building and viewing scheme for modelling together with an anthropometrically and biometrically variable three dimensional model of the human body (Case et al, 1990). A set of human capabilities, including reach, vision and fit is available and the complete system is accessed through a user interface. SAMMIE is described in detail in the following chapter.

Although SAMMIE is possibly the longest established and most widely available man modelling system, many other man-modelling systems have been developed over the years.

To find better solutions to design problems in order to maximise user accommodation a human modelling software that has the capabilities of representing individual users and their capabilities is essential. To evaluate all the individuals in a population this system must be sufficiently fast in accessing the databases and evaluating the design. The SAMMIE human modelling system provides all this capabilities. Additionally SAMMIE is used in the HADRIAN software, which has the ability to determine the percentage of users that have been designed out by evaluating the design using the inbuilt database of individual users. Since it is invaluable to have these data in order to find better solutions for design problems, HADRIAN and hence SAMMIE was chosen as the human modelling system that is used in the proposed new approach for evaluations.

2.8.2 JACK

JACK man modelling software was developed at the Centre for Human Modelling and Simulation at the University of Pennsylvania (Sundin et al, 2000). It provides a 3D interactive environment and features a detailed human model. This includes realistic behavioural controls, anthropometric scaling, task animation and evaluation systems, view analysis, automatic reach and grasp, collision detection and avoidance. JACK also incorporates animation control with scale, colour, camera switching motions and non-uniform scaling of body segments. Another feature is the automatic grasping of objects using a variety of grip styles and motion planning to allow automatic reach and grab motions. JACK enables dynamic forces to be computed through out animated motions and compared against strength data to assess the validity of motions and postures.

Figure 2.15 – A picture of JACK manikin

2.8.3 SAFEWORK

SAFEWORK is another man modelling system that can evaluate potential problems related to posture comfort, motion and posture feasibility, visibility and reachability of controls. Users select critical anthropometric variables for a given population and then one or several 3D manikins are generated, as subjects, from anthropometric data in the database (Fortin et al, 1990). SAFEWORK contains 14 3-D biomechanical models and a small transparent system, which leads the user, with simple questions, to choose the appropriate model for the situation.

2.8.4 TADAPS

TADAPS (Twente Anthropometric Design Assessment Program System) was developed at the University of Twente, Netherlands (Westerink et al, 1990). Within the anthropometric assessment a man model and a workplace model are used. The man model is based upon a simplified model of the human skeleton. It consists of a number of logically linked segments, around which a wire frame man model is created. The workplace model is created by using primitives such a node, wire, block, prism, etc. Various man models are available or can be created. Model percentiles can be chosen. Anthropometric assessment of the workplace involves the transformation of workplace objects and user analysis of 'body clearance and interference', 'reach', 'visual field', for various percentiles, postures, positions and points of view. The anthropometric accuracy of the man model is restricted. The model is an approximation of a non-existent percentile man with defined proportions and the space needed for clothing etc. is not included.

2.8.5 HUMAN

HUMAN is an AutoCAD based human modelling system that can be used in ergonomic evaluation of workplaces (Sengupta and Das, 1996). This three dimensional manikin can accommodate any desired anthropometry and allow flexibility in posture control. Sangupta and Das claim that the main advantage of using HUMAN is it being used within the widely available software AutoCAD. This is because since the human model works on the

AutoCAD platform, the features of a professional CAD system and the human model are simultaneously available to the users.

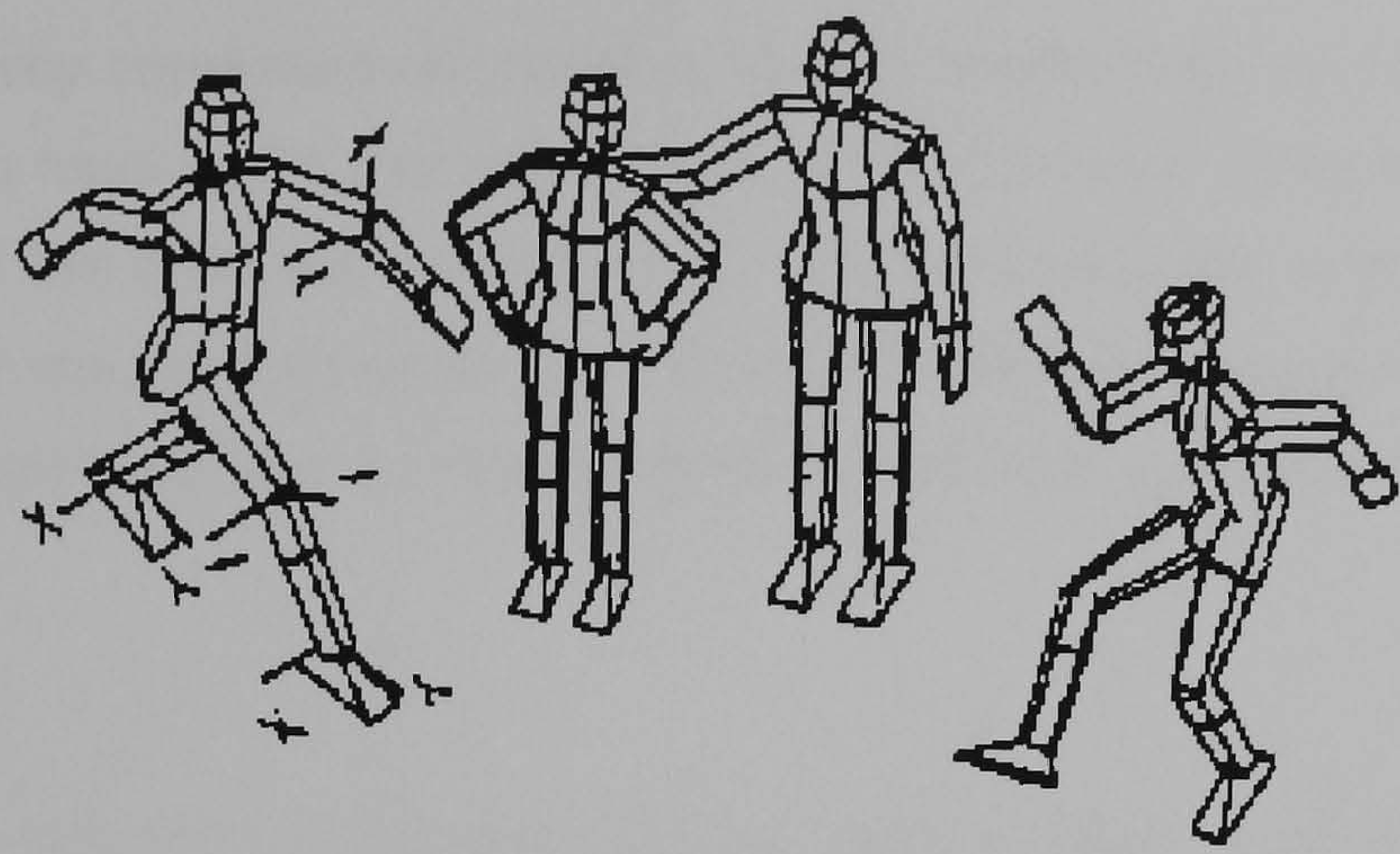


Figure 2.16 – The flexibility of size and posture of the manikins

Many other man-modelling systems are available and some of them, for example WERNER (Kloke, 1990) and ErgoSPACE (Launis and Lehtela, 1990) are relatively recent while others such as COMBIMAN and CREW CHIEF (McDaniel, 1990) have been around for some time. COMBIMAN performs four types of analysis of aircraft pilots, namely, fit, visibility, reach and strength for operating controls with arms and legs. The CREW CHIEF model allows the designer to simulate a maintenance activity on the computer-generated image of the design and to determine if the required maintenance activities are feasible. Both models are currently used in the aerospace industry.

These systems are highly visual and provide ergonomics information that is completely integrated with the computer based design work.

Success of the work depends largely on the designer's use of the system. Consideration of the anthropometry to be used with the model and the ergonomic evaluations depend on the judgment of the designer based upon the experience (Case et al, 2000). One of the limitations in SAMMIE and other human modelling software is that there is no facility to assist the designer to understand how different people actually choose to move and position themselves when performing a variety of reach tasks according to their abilities (Chaffin and Faraway, 2000).

For these human modelling systems to successfully represent the users they must have access to the details of anthropometry of the product users and also their capabilities. Many of these systems incorporate anthropometrics in building of the human model and some include capability and joint constraints as well.

2.9 Conclusion

The literature survey conducted on Inclusive Design practice has shown that inclusively designed products have social and economic benefits to people. Most people who design are now aware of the changing demography of the world and the need for the products that are usable by most of the population. People are also becoming alert about the social and economic advantages that can be gained by developing products that can be used by most.

Many ideas and concepts of Inclusive Design have evolved over the past decades. Increasingly researchers are trying to aid designers to achieve inclusivity in designs. Designers on the other hand were found to be willing to include the details of older and disabled users, if they have easily accessible data and tools to manipulate them.

The Gap in the present design practices of Inclusive Design

Although many theories and a few design approaches have been devised, a specific tool that the designers can use to predict the physical parameters of a design that would maximise the user accommodation is not presently available. This thesis presents a design tool that is specifically built to fill this gap and the theoretical aspects developed in order to create it.

Literature has also shown that the technology to build this tool already exists in the form of human modelling and optimisation methods as well as in ergonomics analysis. The literature review has identified the software available in this area that can be used for this project. The project 'Design for All' has provided the perfect tool in the form of HADRIAN that can be used in this project to build the proposed software tool. The database of HADRIAN and the task analysis features were freely used in the new software.

The next chapter describes the methodologies chosen, that is the constraint modelling and SAMMIE/HADRIAN software system, to conduct the research. The technology available in the field of constraint modelling is also discussed.

Chapter 3

Constraint Modelling and Ergonomic Evaluation to achieve Inclusive Design

3.1 Chapter Overview

In this chapter, the methodologies chosen to implement the new Inclusive Design approach are described, especially constraint modelling and its implementation through the software SWORDS. Furthermore, SAMMIE the human modelling system chosen to perform the ergonomics evaluations in conjunction with HADRIAN is described. Also the ergonomics principles used in the analysis of reach, fit and vision are explained with a view as to how they are applied in these software.

3.2 Constraint Modelling

Design is quite often an activity of satisfying constraints. In the beginning of a design process, even when the precise rules that govern it are not yet fully understood, a set of constraints that bound what can be done is often clear (www – Bath University). According to Mullineux (2001) constraint modelling theories have originated from these situations where researchers have tried to model a design with known constraints that bound a subset of feasible designs. These constraints can be limitations of weight, size or allowable forces etc. A fully acceptable design lies in the intersection of all these subsets. If the intersection is empty, then the skill of the designer is in deciding which constraints can be relaxed with safety (Mullineux, 2001).

Constraint modelling techniques have been used in many areas. For example Young et al (1992) describe a constraint modelling system called SPARK that has been used in concurrent engineering. Cormier et al (1998) have developed an algorithm that merges constraint modelling and genetic algorithms to solve concurrent engineering problems. Dominic is a constraint modelling system that is being used to solve mechanical engineering problems (Howe and Cohen, 1986). In this thesis however, the focus is on the constraint modelling techniques that are applied to geometry modelling since geometry modelling is the most relevant area where constraint modelling has been used with regard to the research discussed.

Constraint modelling has frequently been applied to sketching software. In these software the main attention was given to the constraints relating to the geometry involved, particularly in relation to the underlying Cartesian coordinates of points. Modelling with constraints involves defining constraints that are applied to the feature structure and the boundary representation (BRep) structure of the solid models as well as geometry of objects as illustrated in Figure 3.1 (Anderl and Mendgen, 1996). Anderl and Mendgen explain that in a CAD system, as well as the constraints applied to the geometry of products or parts, the constraints applied to the parameters representing other product information such as material properties or technology and manufacturing properties must also be modelled. They subdivided all these constraints into geometric constraints and engineering constraints.

Engineering constraints include parameters like dimensions, material strength and machining parameters such as cutting speed or feed rate (Anderl and Mendgen, 1996). These can be expressed using arithmetical or functional logical expressions, thus adding engineering knowledge to the product description. Geometric constraints refer to the constraints applied to geometric coordinates or parameters of objects.

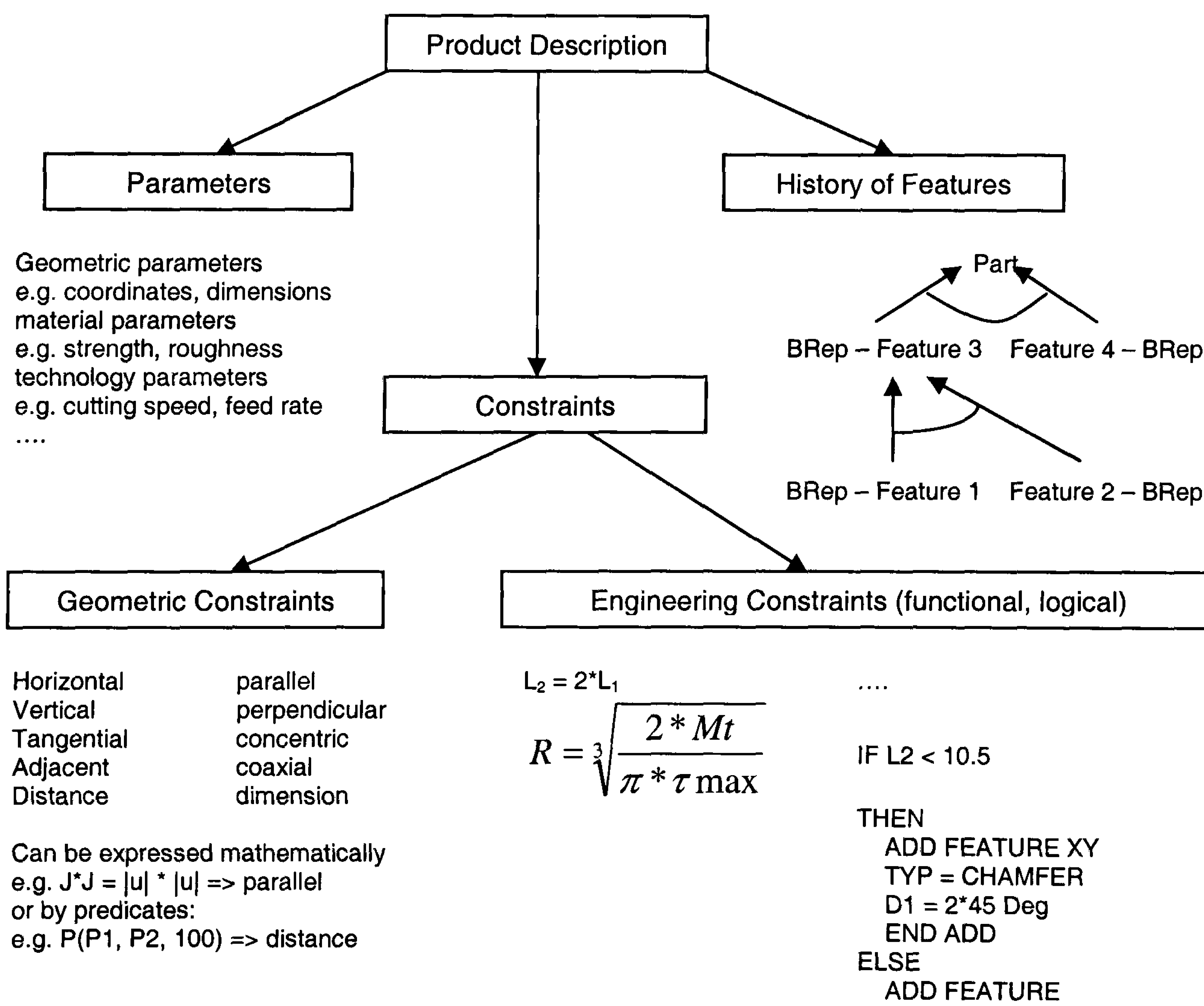


Figure 3.1 – Constraint based product description (Anderl and Mendgen, 1996)

There are two ways of applying constraints. Constraints may be applied to objects by the designer or constraints may be detected automatically by the software (Anderl and Mendgen, 1990). Many CAD systems for sketching support both techniques by enabling the system to detect some geometric constraints by evaluating a rule base and by allowing the designer to define additional geometric, dimensional and engineering constraints. Hoffmann (1994) explains that the rule base approach applied to sketching software has a set of rules for the position and orientation of sketched objects relative to each other or absolute to a given coordinate system. These rules try to recognise the designer's intention and they succeed if the sketch is close to the intended precise shape. Otherwise the rules fail because the system cannot detect the precise rule or the system detects a constraint the designer did not want to apply (Hoffmann, 1994).

3.2.1 SWORDS

The SWORDS constraint modelling software, which is essentially a research tool, uses these constraint-modelling ideas in areas such as design synthesis and optimisation of mechanism and machine systems and to solve many general design problems. SWORDS software allows users to define variables of a problem and then to specify the constraints between them. The software will then automatically search for the configurations, which would satisfy these constraints. In the user language, which has features of BASIC and C languages, - the software itself is written in C - the constraints are specified within 'functions' (Kenney et al, 1997). Functions also contain lists of variables, which the system is allowed to modify while searching for a solution.

Typical mathematical optimisation problems contain objective functions of several variables subject to certain constraints between the variables, which must be satisfied (Arora, 1989). SWORDS uses a method that uses penalty functions. In this method the constraint relations are added in to the objective function to reduce the problem to one of unconstrained optimisation (Mullineux, 2001). This method as described by Mullineux is given below.

If there are n variables $x_1, x_2, \ldots, x_n$ involved in m constraints they can be denoted as follows.

$$f_j(x_1, x_2, \ldots, x_n) \text{ for } 1 < j < m$$

Assuming that these are equality functions or by writing inequalities in that form using ramp functions, the objective function is formed by taking the sum of the squares of these constraints.

$$F(x_1, x_2, \ldots, x_n) = f_1^2 + f_2^2 + \ldots + f_m^2$$

This is a non-negative function and if values for the variables can be found which make F zero, then all the constraint relations have been satisfied. Mullineux suggests that if a minimum can be found which is not zero then the constraints are in conflict and the solution found represents a best compromise.

This method has resulted in a constraint modeller which uses a concept known as 'truth maintenance', where the mathematical function that models each constraint has the value zero when it is fully satisfied (or true) (Medland et al, 1997). Searching for a best solution is carried out using an optimisation technique.

Out of the many well-known methods that deal with unconstrained optimisation, SWORDS uses the Powell and the Hooke and Jeeves methods and variations that use random starts.

3.2.1.1 The Method of Hooke and Jeeves

A flow chart of this method, which dates back to 1961, is shown in Figure 3.2. The search for the optimum solution consists of a sequence of exploration steps about a base point which if successful is followed by pattern moves. This procedure as described by Bunday (1984) is given below.

- First an initial base point b_1 is chosen together with a step length h_j for each variable x_j where $j = 1,2....N$
- Then an exploration about b_1 is carried out to acquire knowledge about the local behaviour of the function. This knowledge is used to find a likely direction for the pattern move by which it is hoped to obtain an even greater reduction in the value of the function. The exploration about b_1 is carried out as indicated below.

  I. Evaluate $f(b_1)$

  II. Change each variable in turn, by adding the step length. That is evaluate $f(b_1 + h_1 e_1)$ where e_1 is a unit vector in the direction of the x_1- axis. If this reduces the value of the function, replace b_1 by $(b_1 + h_1 e_1)$. If it does not, find $f(b_1 - h_1 e_1)$ and replace b_1 by $(b_1 - h_1 e_1)$ if the value of the function is reduced. If neither step gives a reduction leave b_1 unchanged and consider changes in x_2 etc. After all the variables have been considered a new base point b_2 is found.

III. If $b_2 = b_1$ then the exploration is repeated around the same base point b_1 with a reduced step length, usually to one tenth of its former value.

IV. If b_2 is not equal to b_1, a pattern move is made.

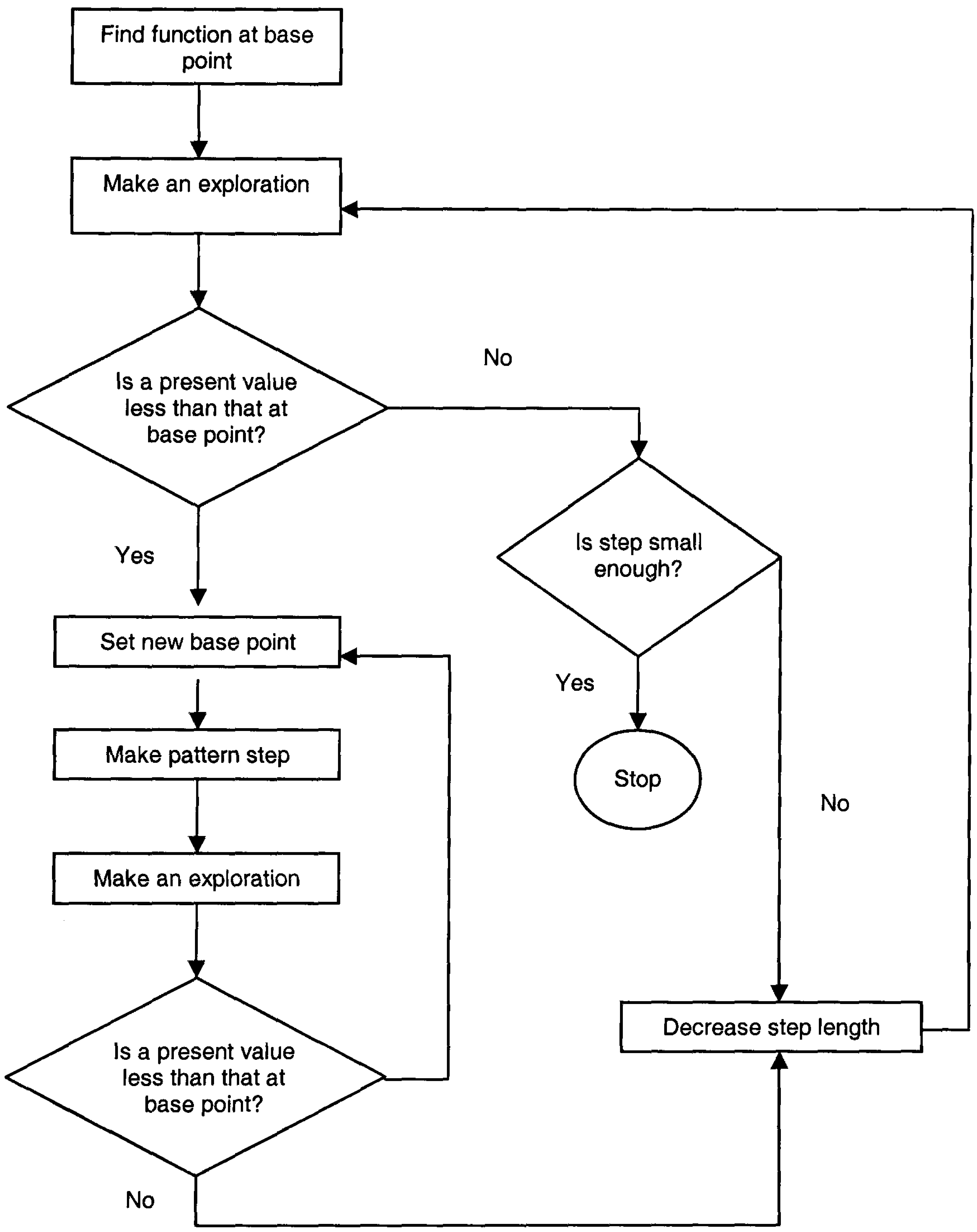


Figure 3.2 - Flow Chart for the method of Hooke and Jeeves (Bunday, 1984)

- Pattern moves utilise the information acquired by exploration, and accomplish the function minimisation by moving in the direction of the established 'pattern'. This is achieved by:

  (a) By moving further from the base point b_2 in the direction $b_2 = b_1$ evaluate the function at the next pattern point

$$P_1 = b_1 + 2(b_2 - b_1)$$

In general, it is, $P_i = b_i + 2(b_{i+1} - b_i)$

(b) Then continue exploratory moves about $P_1(P_i)$.

(c) If the lowest value at the above step is less than the value at the base point b_2 or in general b_{i+1}, then a new base point b_3 or b_{i+1} in general, has been reached. In this case repeat step (a). Otherwise abandon the pattern move from b_2 or b_{i+1} in general and continue with a exploration about b_2 or b_{i+1} in general.

- Terminate the process when the step length has been reduced to a pre-determined small value.

The SWORDS user language is an extension of previous work carried out as part of an earlier constraint modelling system (Kenney et al, 1997). Kenney at al describe that as in a conventional programming language, variables for SWORDS can be declared of types such as real numbers, integers and character strings. Furthermore, simple two and three-dimensional graphical entities are available such as lines and circular arcs. Using SWORDS user language expressions between variables can be evaluated. Constraints can also be defined in terms of expressions. The optimisation methods described above are used to adjust design variables, selected by the user to minimise the overall value of the constraints.

3.2.1.2 SWORDS software environment

SWORDS allows the user to group design parameters and constraints together in cells that are set up hierarchically in a way similar to the directory structure for disc files. The root cell represents the overall design while the cells below it represent sub problems that need to be solved. The constraints within a cell usually relate to the variables within it but they can also reference design variables in other cells. Constraints, which are first defined separately within a cell, are then formed into groups together with the design parameters. These parameters can be changed when constraints are resolved.

A graphics window can be invoked in SWORDS to display the graphical entities. This allows the current state of the design to be visualised. Animation of the functions of a machine being designed can also be set up. A graph window allows the user to display in graph form any results of analysis or constraint resolution.

SWORDS can communicate with external software, and can also be used to carry out solid modelling operations and by allowing interaction between external software, optimisation of design factors such as forces can also be carried out.

The main attraction of SWORDS is that it is able to handle all the various different types of constraint within a single unified approach. The SWORDS solution method does not depend on the specific forms of constraint.

The disadvantages of the approach used in SWORDS are that the search may settle on a local minimum, which is non-zero. Then it is hard to know from the mathematics alone whether no overall solution exists or whether the search has simply missed it. The way out of this is the human user's intervention and if necessary the starting of the optimisation process from a new start point. The search only looks for a single solution and if multiple solutions exist they are ignored. This can be used to advantage in under constrained situations where there can be an infinitely many solutions (Mullineux, 2001).

3.2.1.3 Applications of SWORDS

SWORDS has found many applications in assembly modelling, packaging design, and mechanism design as well as more recently in constraint based manikins (Medland, 2000). An example of the projects undertaken using SWORDS is, the mechanism

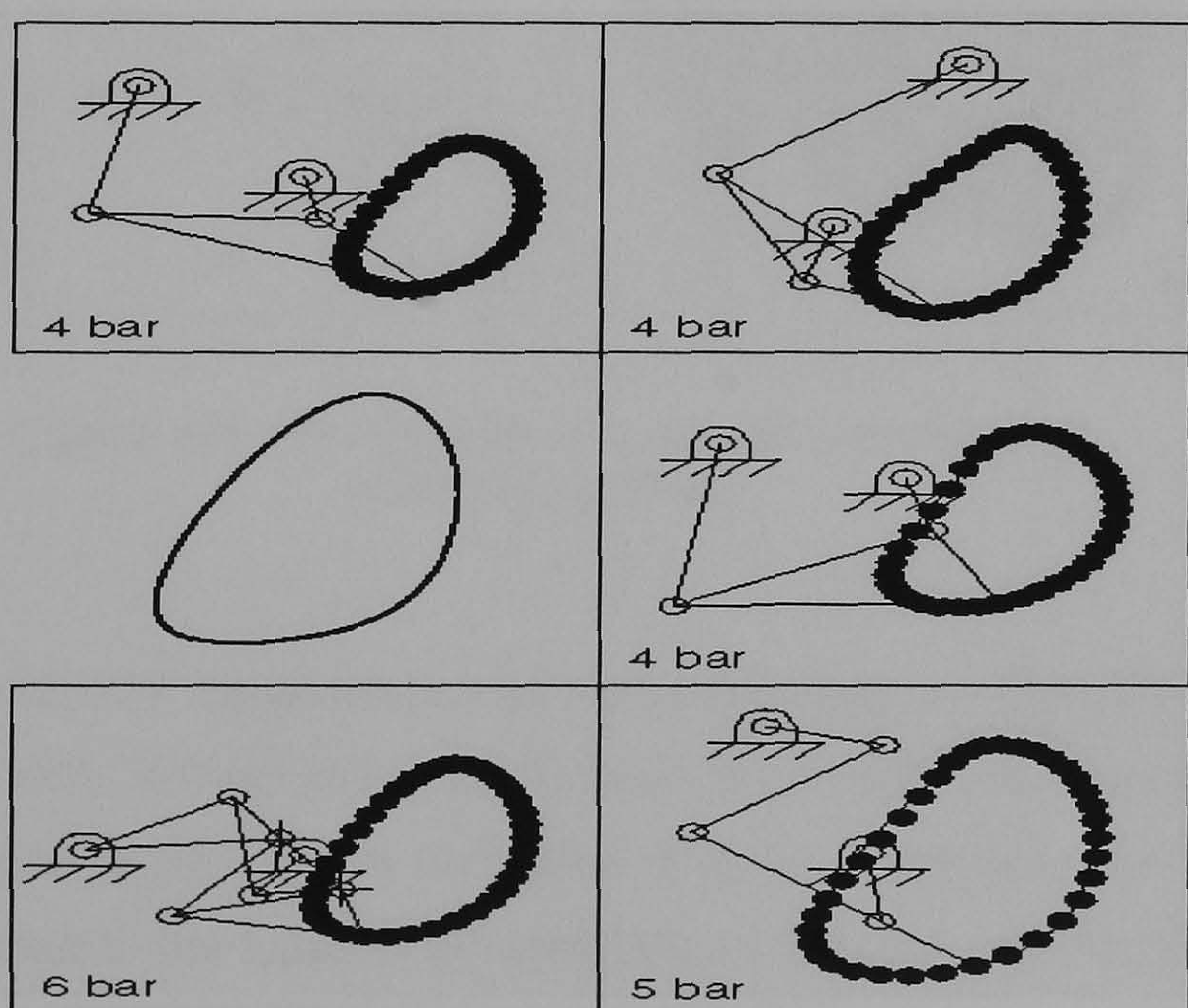


Figure 3.5 - SWORDS Mechanism Selection (www – University of Bath)

selection shown in Figure 3.5. SWORDS allows mechanisms to be chosen and optimised to meet given motion requirements. Here a closed curve has been specified by the designer (www - University of Bath). Five different mechanisms capable of generating a close approximation to the given path are shown. These (and others) were proposed by the system. Further constraints could be added and the motion and/or the mechanisms refined.

Mullineux (2001) provides an example of SWORDS use in mechanism modelling as shown in Figure 3.6. It shows a simulation of a six bar mechanism that SWORDS has assembled. Figure 3.6(a) shows the 'stick diagram' representing the six bars. Figure 3.6(b) shows the model spaces SWORDS has used in order to assemble this and also the hierarchy of the model spaces. As well as mapping geometry into world coordinates, a model space can also map into another model space. A hierarchy of spaces can be created in which each embeds into another to form a tree structure. The root of the tree is world space. Figure 3.6(c) shows the initial assembly of the mechanism with more detailed two-dimensional wire frame geometry. Figure 3.6(d) illustrates one cycle of the motion.

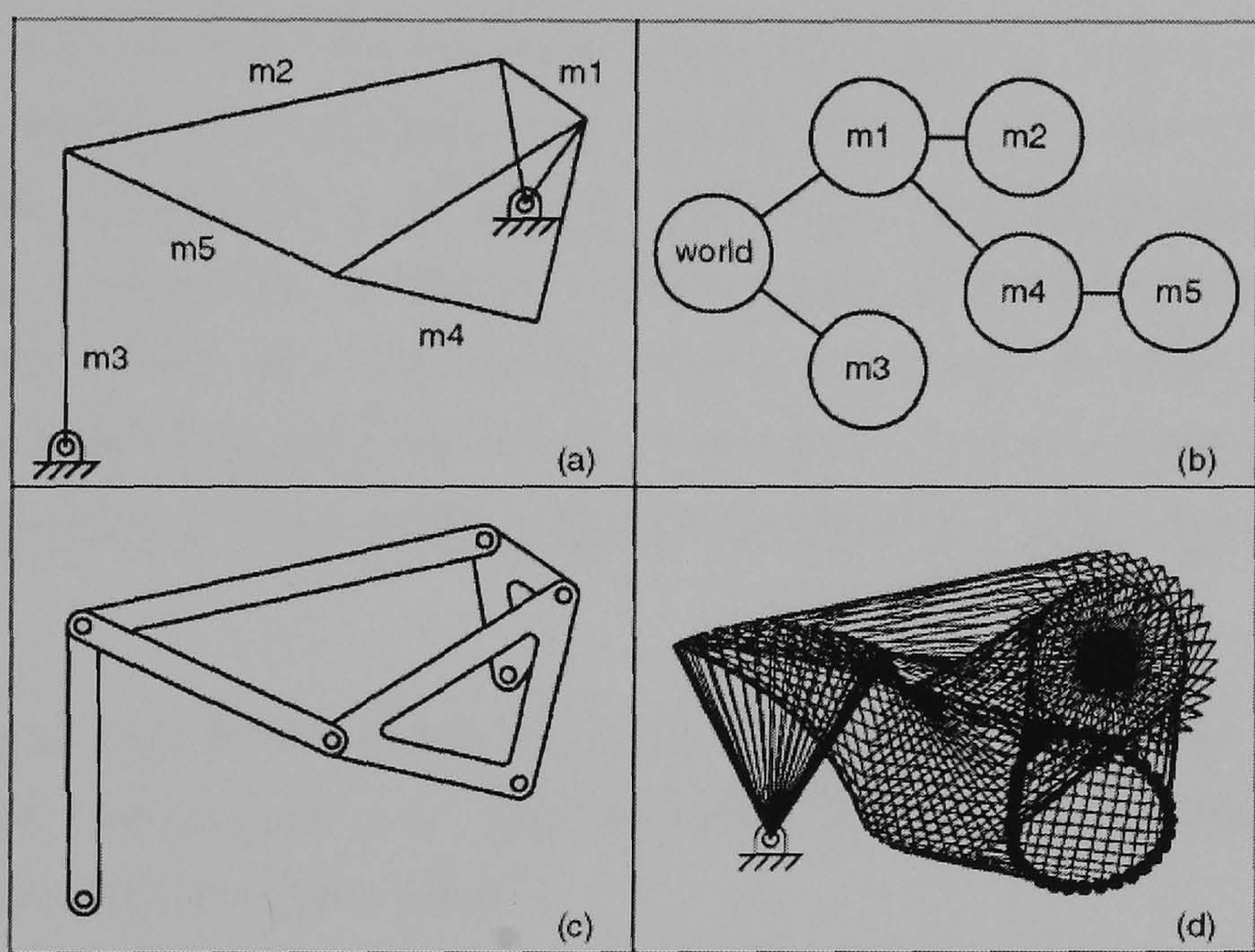


Figure 3.6 - Simulation of a six bar mechanism (Mullineux, 2001)

In summarising SWORDS capability it can be stated that the SWORDS system allows variables and geometric entities to be defined and constraints imposed on them. Then an optimisation technique is used in the resolution of these constraints. As shown above the system can be applied to the types of problem encountered in constraint-based assembly modelling systems and mechanism simulation. Also solid objects can be defined by the SWORDS system and manipulated with other variables.

SWORDS's ability to handle a large number of variables can be used in resolving multivariate problems that occur when considering individual users in Inclusive Design problems. Since these problems involve a large number of constraints as well, finding a single solution within all the constraints, or if some of the constraints are in conflict finding the best compromise is an important capability that can be used in designing inclusive products and workplaces. Another important capability of SWORDS that can be utilised in solving Inclusive Design problems is its ability to accommodate almost any type of constraint functions as long as they are written in an algebraic form. This is important when specifying the characteristics of the design and the users to the system.

3.3 Ergonomic Evaluations and Human Modelling in Computers

The discipline of modern ergonomics has been around for more than 50 years. Interactions between humans and the workplace have been of interest even earlier than that. Formal consideration of the interactions between people and their working places has been found in writings from ancient Greece, in medieval medical accounts and from Poland and Germany about 100 years ago (Wilson, 2000). Ergonomics is both a science, which provides fundamental understanding, and also a technology, which applies that understanding to problems of design in their widest sense (Shackel, 1996). It can contribute to the solution of a large number of problems related to safety, health, comfort and efficiency. Ergonomics can have a large effect on the Inclusive Design area because ergonomics takes humans into account, as does the Inclusive Design concept.

There are many ergonomics principles arising from disciplines such as biomechanics, physiology and anthropometrics. A few examples of these, as described by Dul and Weerdmeester (1993) are given below.

- Joints must be in a neutral position when maintaining a posture or making a movement. This is because in a neutral position, the muscles and ligaments, which span the joints, are stretched to the least possible extent and subject to less stress. Therefore raised arms, bent neck, bent wrists, bent and twisted trunk are examples of poor postures.
- Keep the work close to the body to avoid outstretched arms and the trunk bent over forwards.
- Alternate postures as well as movements to avoid having prolonged postures and repetitive movements that are tiring and in the long term can injure muscles and joints.

- Avoid bending forward
- Limit the energy expenditure in a task
- Limit the duration of any continuous muscular effort
- Rest is necessary after heavy tasks
- Take account of differences in body size
- Use the anthropometric tables specific for specific populations

The designer needs to have knowledge of these ergonomics principles when evaluating a product or a workplace using human modelling software.

The selection of the human modelling system that is used in this research was based mainly on its capability of handling individual data of product users. Another important criterion was that software's capability of evaluating each and every user individually and automatically. This automation process proved to be a great advantage when more complex workplaces were considered. The only available software that has these capabilities at the moment is called HADRIAN and its details and the software SAMMIE functionality on which HADRIAN is based are discussed here.

3.3.1 HADRIAN

HADRIAN (Human Anthropometric Data requirements Investigation and Analysis) is the outcome of the project 'Design for All'. Marshall et al (2002) describe HADRIAN (Human Anthropometric Data Requirements Investigation and Analysis) as a task analysis tool that combines the capabilities of a computer aided design tool with a database of individuals including the individual users' anthropometry, mobility, capability, disability and coping strategies. Most computer-based human modelling systems such as JACK (Sundin et al, 2000) and SAMMIE (Case et al, 1990) provide models with the capability of representing information regarding anthropometry and capabilities of product users and applying it in design situations. However they do not adequately represent people who are older or disabled. Another limitation of these human modelling systems is that they require an inherent understanding of ergonomics principles. HADRIAN was developed to address these needs. In essence HADRIAN is an enhanced version of the SAMMIE human modelling system (Marshall et al (b), 2001).

As described by Marshall et al (2002) the two systems, HADRIAN and SAMMIE, together provide the designer with the ability to:

- 'model a product/environment or import a model generated in another CAD system,
- select a target user base,
- quickly put together a task description with as much or as little data on viewing distance which hand to use etc.,
- run the task analysis with the chosen user base,
- inspect the results of the analysis including the percentage accommodated, who failed what parts of the analysis and why the failure occurred,
- modify the design/task parameters and re-run the analysis for comparative studies.'

In order to achieve these objectives, HADRIAN consists of two main parts.

3.3.1.1 HADRIAN task analysis tool

The approach taken in developing this tool has focused on three areas: data input and manipulation, task description and analysis, result reporting and analysis feedback (Marshall et al, 2001(a), Marshall et al, 2002).

The HADRIAN task analysis tool provides the designer with a tool to test their products or workplaces using the computer-generated models of individual users of those products. It provides the facility to construct a description of tasks for the interaction with the chosen product or workplace. After loading the desired model into the HADRIAN system, the designer builds the task structure by specifying the task element such as reach or look and the object to be reached (e.g. the pan). Figure 3.7 shows a screenshot of the HADRIAN task builder. It illustrates HADRIAN's capability of providing the designer with the abiity to enter the details of the task such as which hand to use, the viewing distance or the type of grip or whether right or left side of the body is to be used.

The designer can provide a very detailed task or a task with little detail. The information that the designer has not specified but the system needs, to perform the task will be set to a default that is based on the task analysed (Marshall et al, 2002). Even when a system default specifies the nearest hand to use for a reach of a certain object, if the user under analysis has a specific requirement for a particular hand, e.g. the individual is right handed, then the system default will be overridden and the user detail used in the analysis. Therefore after the designer has chosen the user database the designer need not know all the details of the users because the system provides them automatically in the evaluations.

Marshall (2000) explains that although most of the tools for HADRIAN task analysis are based on SAMMIE's functionality, the HADRIAN task analysis tool has taken over the driving of the models from the designer. By doing this and by applying in built sound ergonomics principles in analysing the tasks HADRIAN has also provided the designer with a powerful and flexible tool. Designers who use this CAD system no longer need to be ergonomists as well. They can then concentrate on the product and the tasks that the users have to perform with it. Also they need not have a detailed knowledge of how to drive the SAMMIE system.

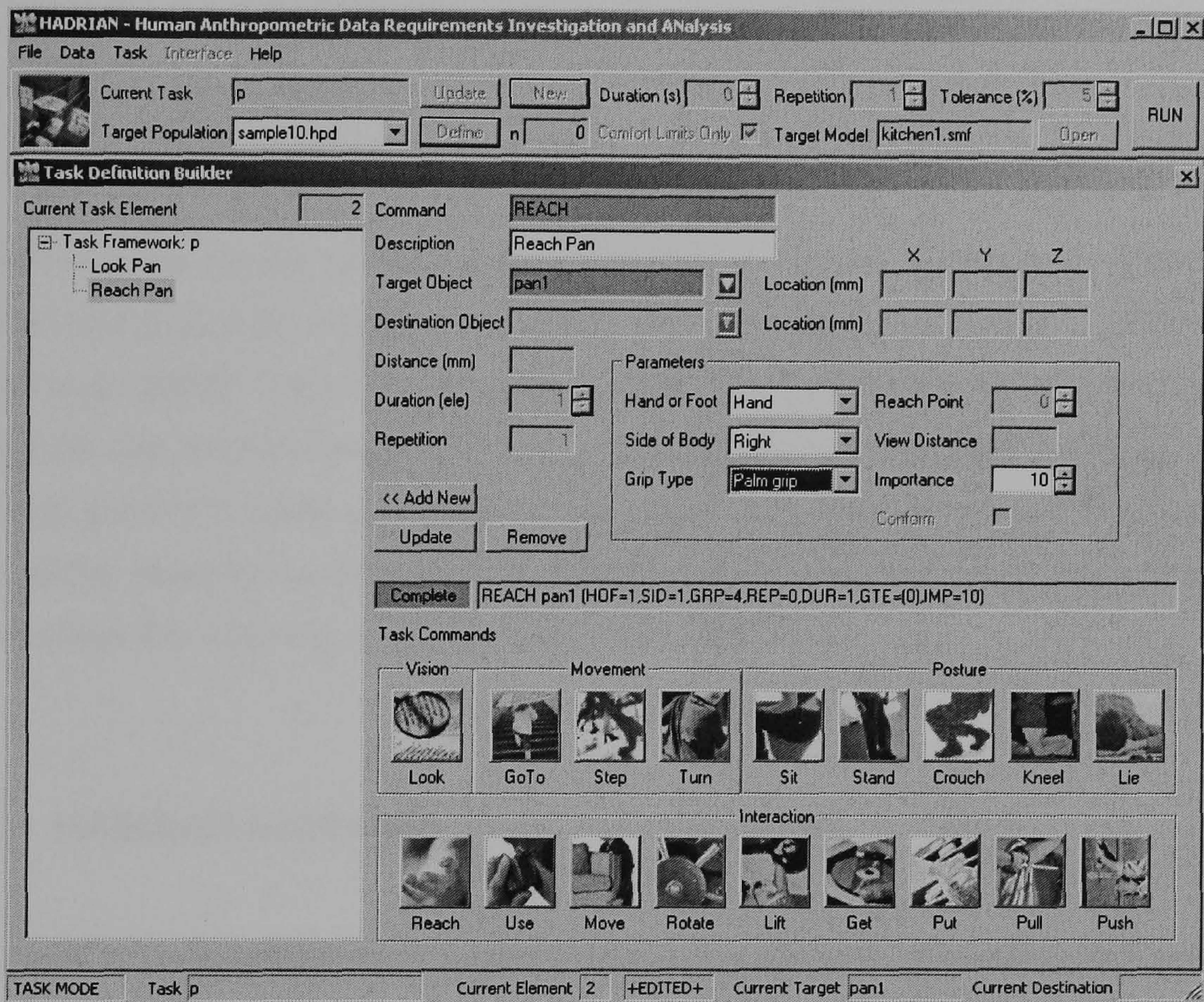


Figure 3.7 – A screenshot from the HADRIAN task analysis tool

According to Marshall (2000) HADRIAN achieves this by utilising the SAMMIE macro language. Using macros it can select successive data on each individual and modify the human model to use in the evaluations, according to those data. Then it uses a set of system commands, which are interpreted by the system into a set of internal SAMMIE commands. These system commands consist of a key word, a set of optional controlling parameters and a target or value (Marshall, 2000).

To achieve all this the HADRIAN system needs a wealth of information. It receives information from three main channels through human models, task descriptions and the model of the task environment. The selection of target objects for the task description is from a model file listing. By allowing this to be an interactive process the system ensures that all the necessary information is provided for the task analysis (Marshall, 2000).

The HADRIAN task analysis tool can be used in two ways (Marshall et al, 2002). One way is to allow the system to perform the analysis without any user intervention. In this case the system makes assumptions where required and skips failures to carry out the whole task structure the designer has specified. The results are presented after the analysis. The second way is for the designer to be involved in the decision making process by deciding what to do when a task has failed etc. This allows the designer to refine the task analysis or by viewing the analysis step by step the difficulties faced by each user can be understood and take remedial action.

HADRIAN logs the results of task analysis and reports the key variables that are involved in a failure and directs the designer's attention to the fundamental reasons for the problem (Marshall et al, 2002). Thus it reports who has been designed out and why. A summary of these results can be obtained in the form of the percentage accommodated by a design. Percentage accommodated in a design is the percentage of the population that are able to perform all the essential tasks needed to successfully interact with the design. This can be used to assess the usability of various designs of a product.

3.3.1.2 HADRIAN database

An important feature of HADRIAN is that it contains a multivariate database of individuals, which includes anthropometric and mobility data and video of task behaviours and capabilities for the designer to be more familiar with the user. The advantages of this are two fold. On one hand it familiarises the designer with the user population without directly involving the users. This enables the designer to create better designs to suit all users, which can involve design changes such as using ramps to access a building rather than steps or using adjustable heights for shelves in a kitchen. On the other hand it gives a rich database of all the individuals for the design evaluation process. Figure 3.8 shows a graphical representation of data regarding a user in the HADRIAN software.

HADRIAN also provides information on each user's anthropometry, joint movements and capability of performing various tasks. The database contains details of most of the joint movements including shoulders, upper arm, lower arm, wrist and legs. It provides individual user's capability of performing tasks such as bending, grip strength, left and right twist of the upper body and reach envelopes.

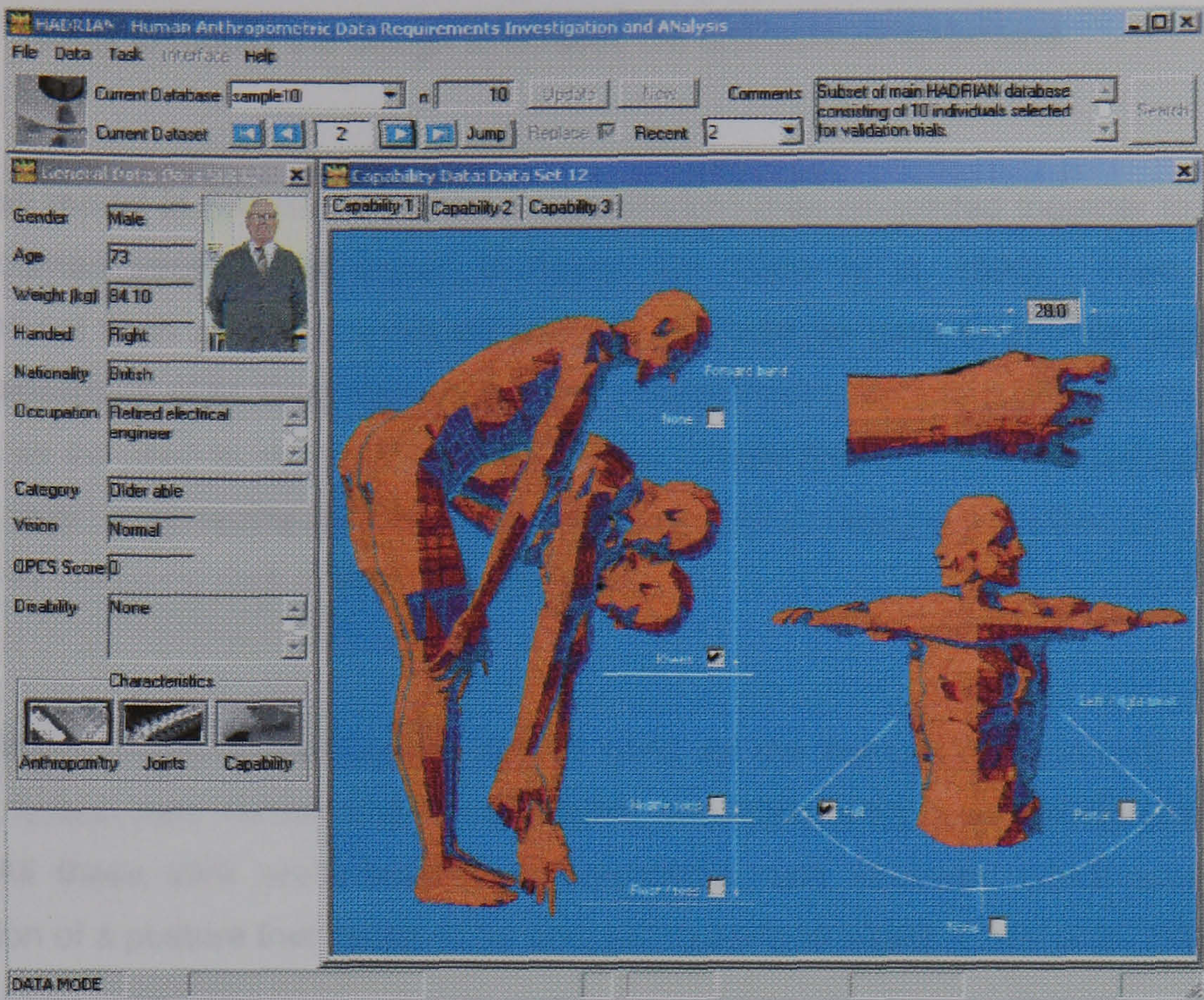


Figure 3.6 - A Screenshot of HADRIAN Showing anthropometry details of a user

HADRIAN is a prototype tool and still in development. However most of the above-mentioned features are fully functional and can be used in evaluations of products and workplaces. The main limitation of HADRIAN is that although it reports the user accommodation and where the problem could be, it does not have the capability to predict the design parameters that increase user accommodation. This is being rectified by this research.

3.3.2 SAMMIE

SAMMIE is the computer aided human modelling system whose functionality has been enhanced by HADRIAN. SAMMIE can be used to assess the postural constraints placed upon people when interacting with the designed physical environment. The basic functionality provided in SAMMIE, in brief, are (Case et al, 1990):

- 3D modelling of people of the required sex, age nationality and occupational groups.
- A knowledge base of comfort angles for the major joints of the body together with joint movement constraints to represent human capabilities.
- Ability to model 3D workstations with added ability to simulate the model functionality such as ranges of adjustment, control operation ranges, and the structural and functional relationships between the model elements.
- Ability to assess the interaction between the human model and the workstations in terms of user fit, reach, vision and detection of interference.

- Ability to modify the design to achieve the optimum compromises.

The man model in SAMMIE consists of rigid straight links pin-jointed together to form the basic human structure as shown in Figure 3.9 (Case et al, 1990). Then a three-dimensional flesh shape is arranged about it. This can be used to provide visualisation and assessment of fit. Data files contain the anthropometric data and joint constraint data, which can be used to modify the human model. These files can be modified or replaced by the user. This facility can be used when evaluating designs for older and disabled people by replacing data in this file by their data.

The SAMMIE man model has the similar parts as the human skeleton and it models ankles, knees, hips, lumbar and thoracic spine, shoulders, elbows, wrists, neck, head and eyes. All these data are placed in a hierarchical data structure, which enables the prediction of a posture that needs to be adopted to perform a task (Case et al, 1990).

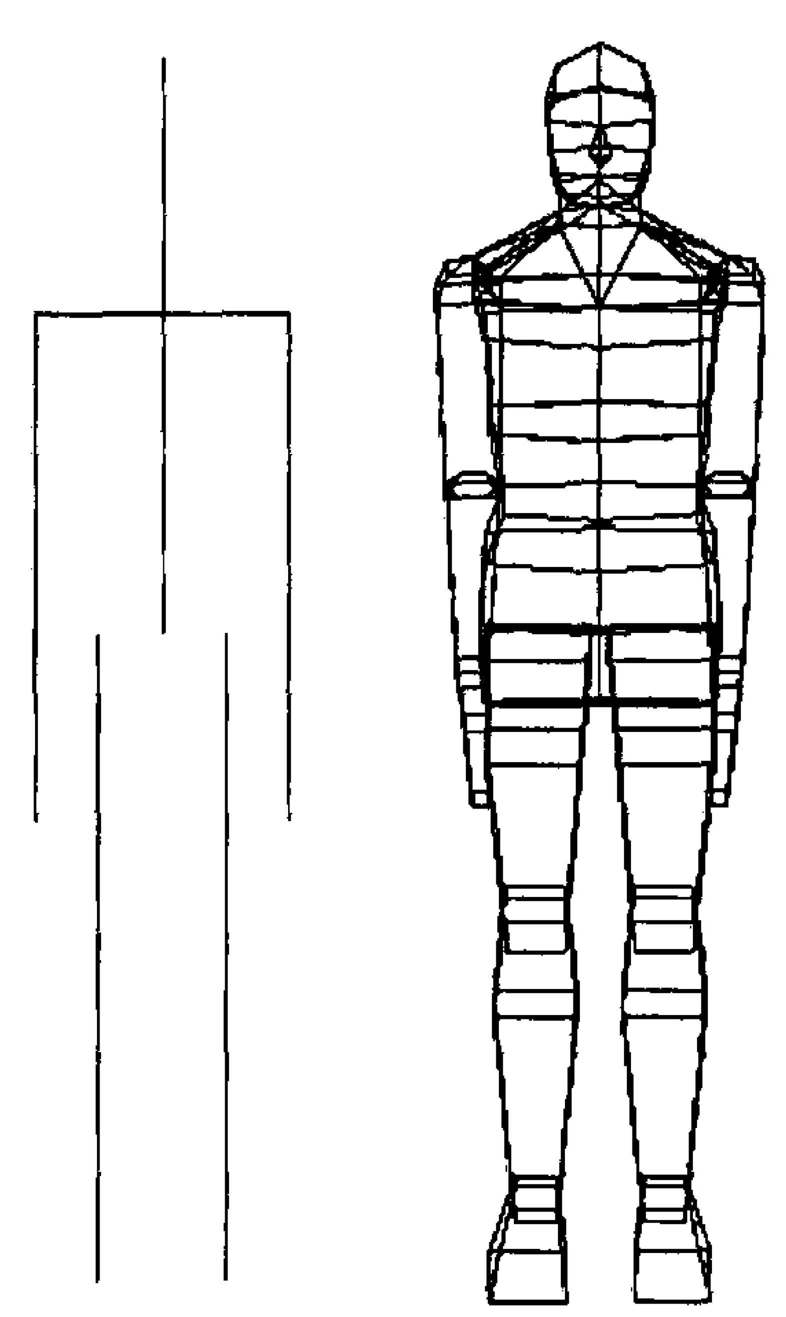


Figure 3.9 –SAMMIE stick man and flesh man

Over the years SAMMIE has been used in many ergonomic evaluations for industry (Porter et al, 1999). For example, Figure 3.10 shows a SAMMIE model used in the design of the Brussels Tram 2000. SAMMIE was used to help in the design the cab of the driver to allow optimum visibility, driving and selling tickets. Another example in Figure 3.11 shows a SAMMIE model used for the design of the Rotterdam Metro cab. Here SAMMIE's reach and vision capabilities were used to design the controls.

Figure 3.8 - STIB Brussels 2000 Tram cab (www – SAMMIE)

Figure 3.9 – SAMMIE design of Rotterdam Metro cab and its mock-up(www – SAMMIE)

3.3.2.1 SAMMIE Ergonomics Analysis

SAMMIE, with its anthropometrically sound human models and geometrically correct workplace modelling capability provides a tool the designer can use to test the ergonomic principles described above. SAMMIE human models provide the joint constraints and warn the designer if the human is strained beyond the normal limits. However the designer must have a knowledge of ergonomics principles to apply to these models. E.g. designing to avoid excessive reaches in forward and sideways directions to avoid twisting the trunk etc.

Case et al (1990) describe two ways of obtaining the required postures within SAMMIE. One is to use an object-oriented method such as reach for particular object with a particular hand or look at a certain object. The SAMMIE human model will try to reach or look and in doing so it will assume a posture within the joint constraints. But in order to do this the model does not bend or twist the trunk as a real person would. The other way is for the designer to move the parts of the human model in steps until it reaches the required posture. This provides realistic postures that can be used in evaluations.

Each user has to be tested by the designer manually, which is fine for the traditional way of designing for the 5th percentile female and 95th percentile male. But when individual users of products are considered this method proves to be rather difficult and time consuming. Hence HADRIAN has taken over the application of ergonomics principles and individual evaluation. This process uses the following functionalities of SAMMIE in its evaluation.

Reach

Posture of the individual is imposed by the task and the workplace. Ability to reach objects is one of the most important criteria for successful task completion. The SAMMIE system has the capability of evaluating whether the specified human model is able to reach a given object or a given point in space. If the SAMMIE human model fails a specified reach task the system displays that it has failed and also the failed distance.

SAMMIE can also draw reach areas and reach volumes for specified postures as shown in Figure 3.12. Reach volumes or envelopes are volumes defining reach limits. These volumes enable the designer to visualise the area where controls or objects that need to be reached should be put.

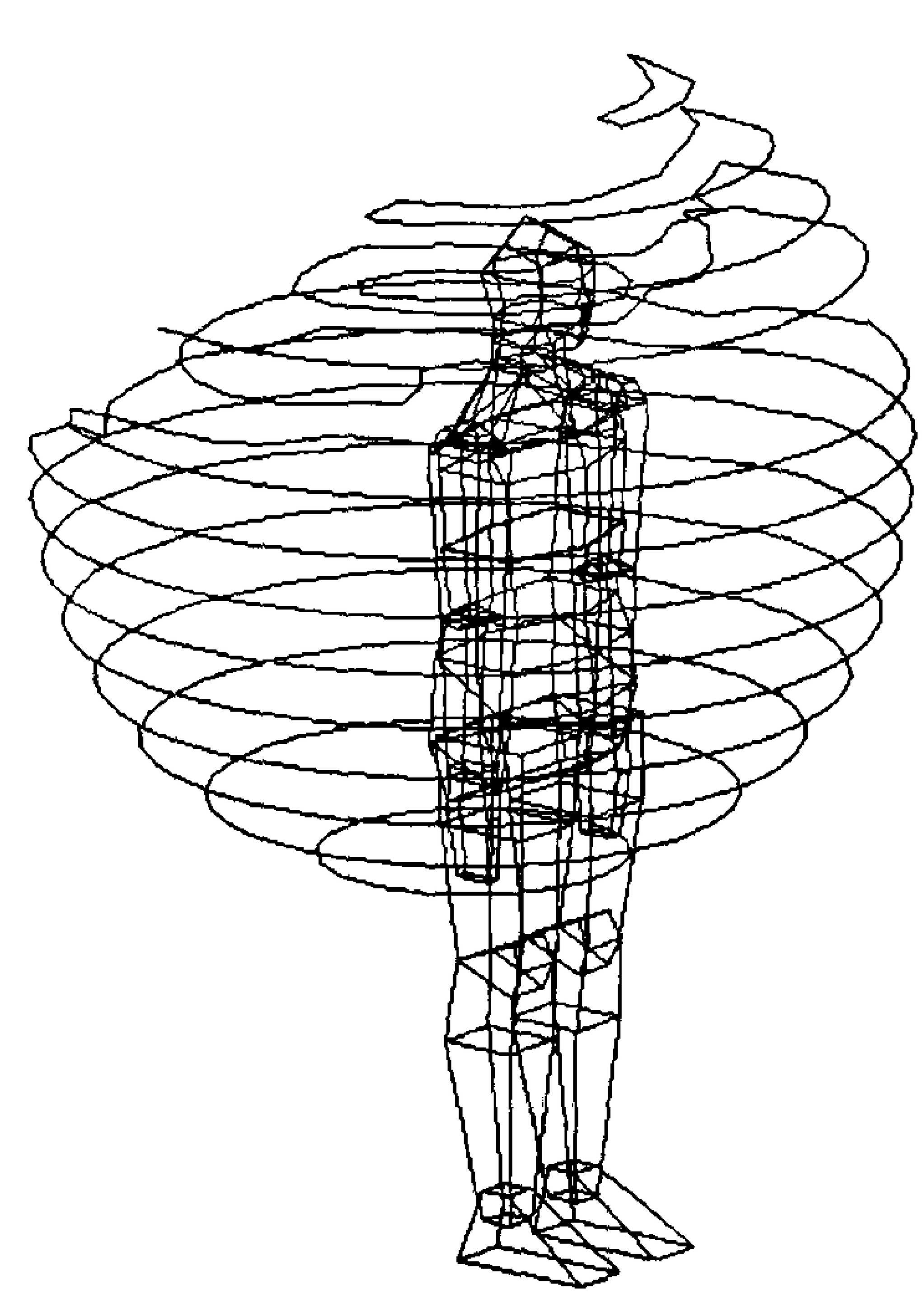


Figure 3.12 – Reach volume with the right hand for a standing model

Fit

Since interference testing is not fully developed in SAMMIE, its ability to evaluate fit is mainly based on the accuracy of the human models and the dimensions of the model of the product. SAMMIE's ability of modelling humans accurately by being able to model each dimension independently plays a major role in this. For example, to evaluate a car seat the drivers who would use it have to be modelled. There are drivers who have long arms but short legs or a tall stature but short arms. Fit is evaluated by modelling these accurately and then using these models in the design environment.

Vision

Vision is an important aspect of design for several reasons. The visual elements of the task determine the posture of the head and neck and also visually demanding tasks may result in visual fatigue and eyestrain. Then the visibility, conspicuousness, legibility and intelligibility of visual displays may be critical both to working efficiency and safety. Furthermore aesthetics of the visual environment is important to the quality of life (Pheasant, 1996). There are many things that need to be considered for an ergonomically sound visual environment such as lighting levels and nature and location of visual displays. In computer based human modelling systems however the evaluation is limited mainly to whether the human models are able to 'see' the object or if it is out of sight because of joint constraints or if there is anything that obstruct the view.

Vision evaluation of SAMMIE is performed mainly by studying the 'human's view' in SAMMIE environment (www – SAMMIE). This view shows what the human model in the SAMMIE system 'sees' as shown in Figure 3.11. This is very valuable because the designer then can see what the users of various sizes and postures can visualise. This allows the designer to change the design if there are any objects that obstruct the view.

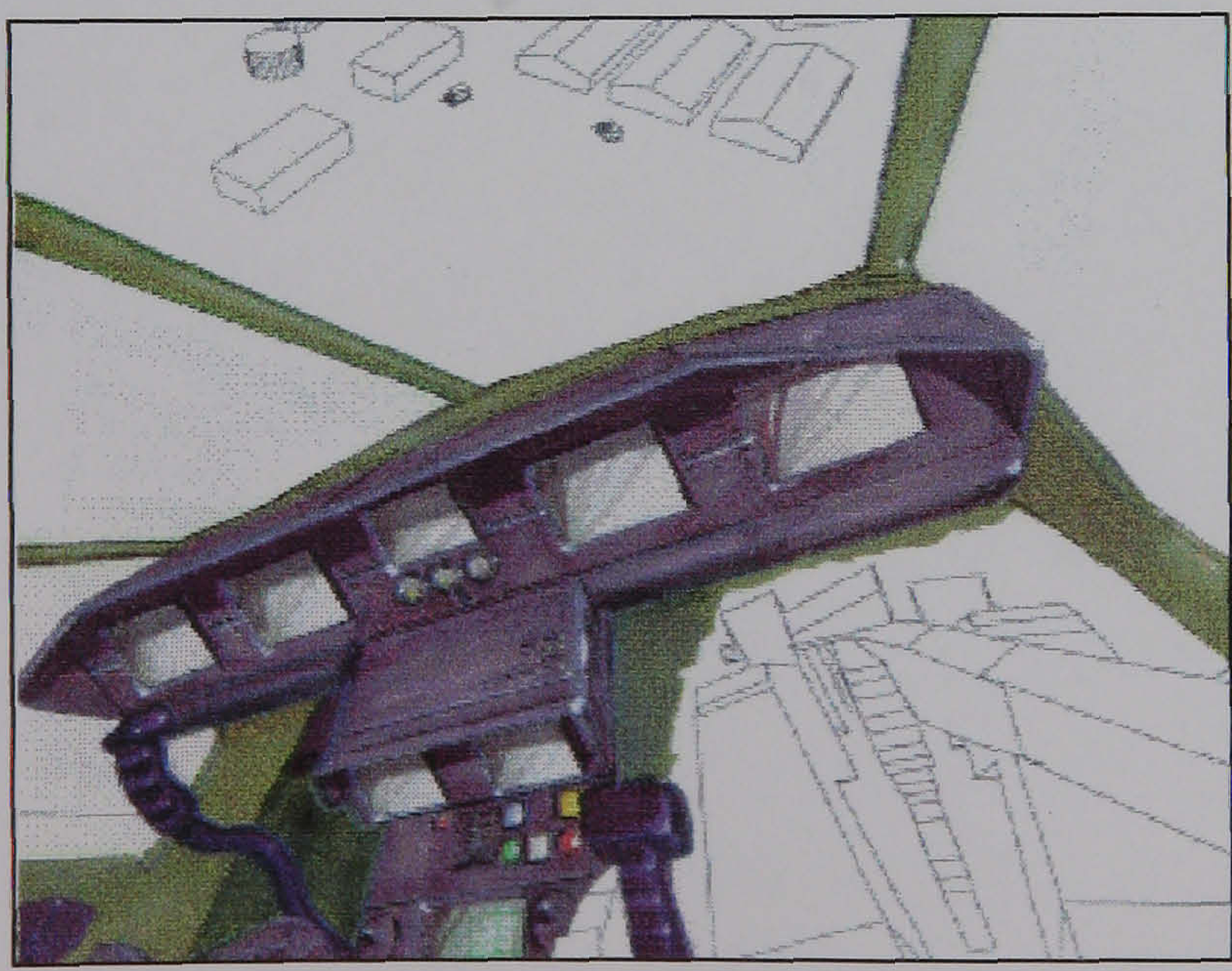


Figure 3.11 – The pilots view from a helicopter model (www – SAMMIE)

The main limitations of SAMMIE are that the designer who uses it needs to have a thorough understanding of the ergonomics required in performing tasks. The use of HADRIAN has eliminated the need for the designer to be an ergonomist to perform evaluations in SAMMIE.

3.4 Summary

In this chapter the technology that can be used to develop a new methodology to implement Inclusive Design has been discussed. The ideas of constraint modelling and optimisation techniques used were discussed in the context of the software SWORDS. Then ergonomic evaluation and a new prototype software HADRIAN that uses SAMMIE functionality was described. SAMMIE was described in order to understand this functionality. The main use of HADRIAN with regard to this research, that is its database of individuals and the ability to evaluate products or workplaces using each individual automatically was highlighted.

The next chapter explains the new methodology developed in this research to implement Inclusive Design concept by considering the users in the design process.

Chapter 4

A New Method for the Optimisation of Physical Aspects of a Design

4.1 Chapter Overview

This chapter provides an overview of the user centred optimum design process. It also illustrates a method that has been developed to incorporate the user in the product design optimisation in order to maximise the user accommodation and describes how inclusive design optimisation problems are formulated to optimise the user accommodation. A brief introduction to the optimum design process versus conventional design process is presented. The chapter concludes with a description of the user-centred optimum design process that has been developed in this research.

4.2 Background

The early attempts of finding better solutions to designs that maximise the user accommodation were focused on the users' flexibility in performing tasks. For example a user normally has the ability to reach an area or a volume instead of a just a point. This is similar for vision and for fit. A method that considered this range of accommodation is described below together with how it failed to solve the problem.When the reach ability was considered the first step in this method was to find the ranges a user could reach in x, y and z directions. Then these were recorded in graphs as shown in Figure 4.1.

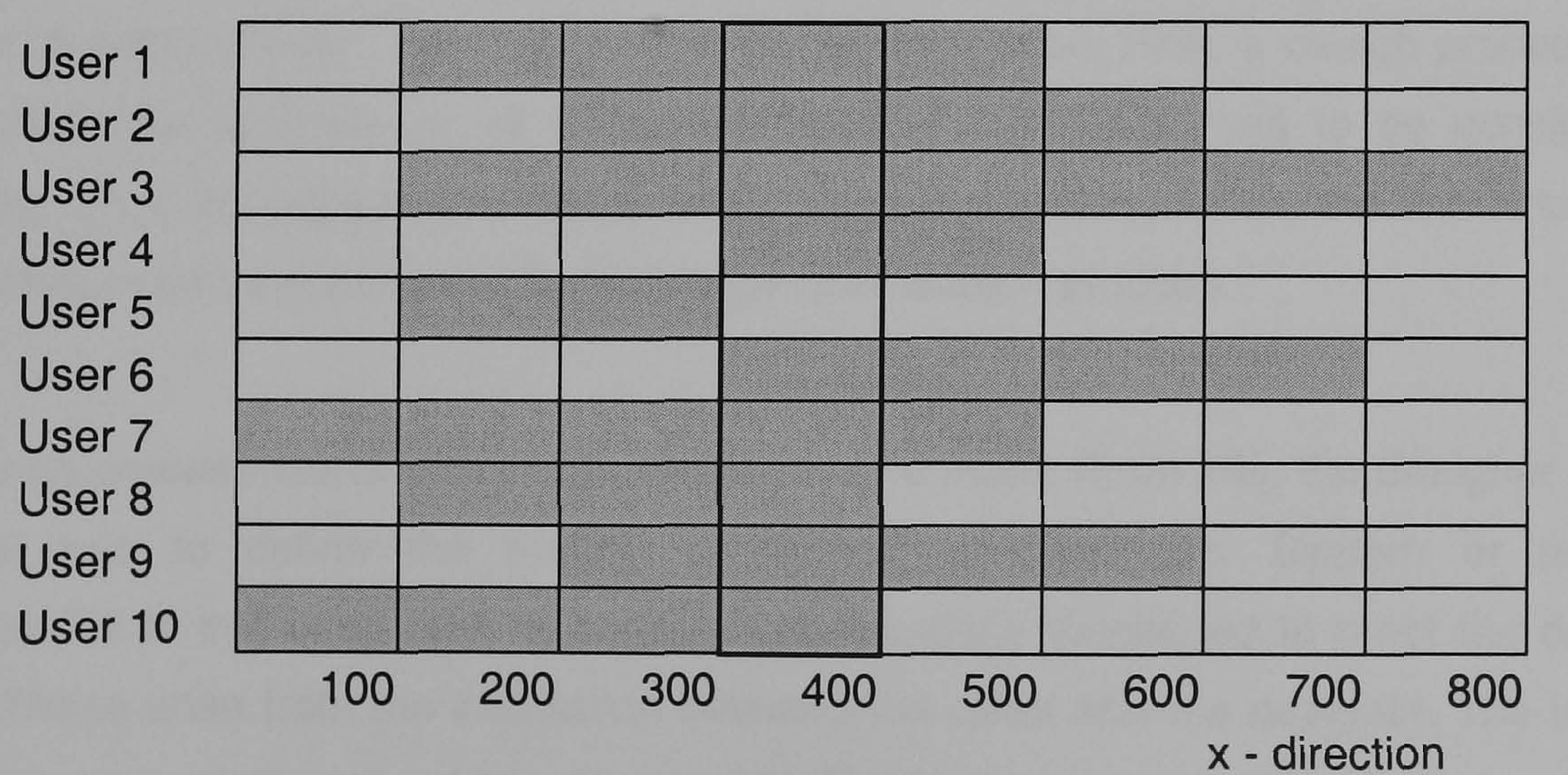


Figure 4.1 - Accessiblity Ranges

This graph shows that all users except user 5 are able to reach between 300mm and 400mm in x direction. These ranges could be found using capabilities of SAMMIE for each user. Then an optimum value for this x variable could be found using the SWORDS constraint modelling software considering the other constraints to the design. The value found by this process is constrained within this accessible range, in this case from 300mm to 400mm. Because this range can be accessible by most of the users it is safe to assume that the optimum value between this range is also accessible by most users hence increasing the user accommodation. Values for variables in other directions can also found be found in similar methods.

However this method only works if the variables in x, y and z directions are independent of each other. If they depend on each other, for example if the value of y variable changes when the value of x variable changes it is difficult to find these ranges. Even if they can be found it is impossible to find values for each variable that satisfies the conditions of the other. This becomes totally unacceptable when more than three dependant variables are considered.

Hence a new approach to the whole problem was envisaged. This technique formulates the total problem as an optimisation problem and finds solutions to it. In the process of this formulation it considers the characteristics of the users as well as the design. This new technique is described below.

4.3 The Optimum Design Process

Optimisation of the user accommodation of a product or workplace is a primary objective of this research. In order to find better solutions to design problems that would maximise the user accommodation, two things need to be considered. First, a design process that would allow the optimisation of various aspects of the design has to be considered. Secondly, since the objective is to maximise the user accommodation, the characteristics of the users must be considered in this design optimisation process.

The design process starts with the identification of a need. From this, the designer or the engineer has to define the system or product specifications. System or product specifications in this case refer to suitable specifications developed to meet the defined needs. These arise from the interaction between the client and the designer. The task of designing can start only after these specifications are defined precisely. These specifications lead to a preliminary design, which in turn becomes the detailed design of the product or the system. In order to achieve the best, most cost effective, efficient, reliable, and durable and above all usable design, the designer may need to analyse several trial designs.

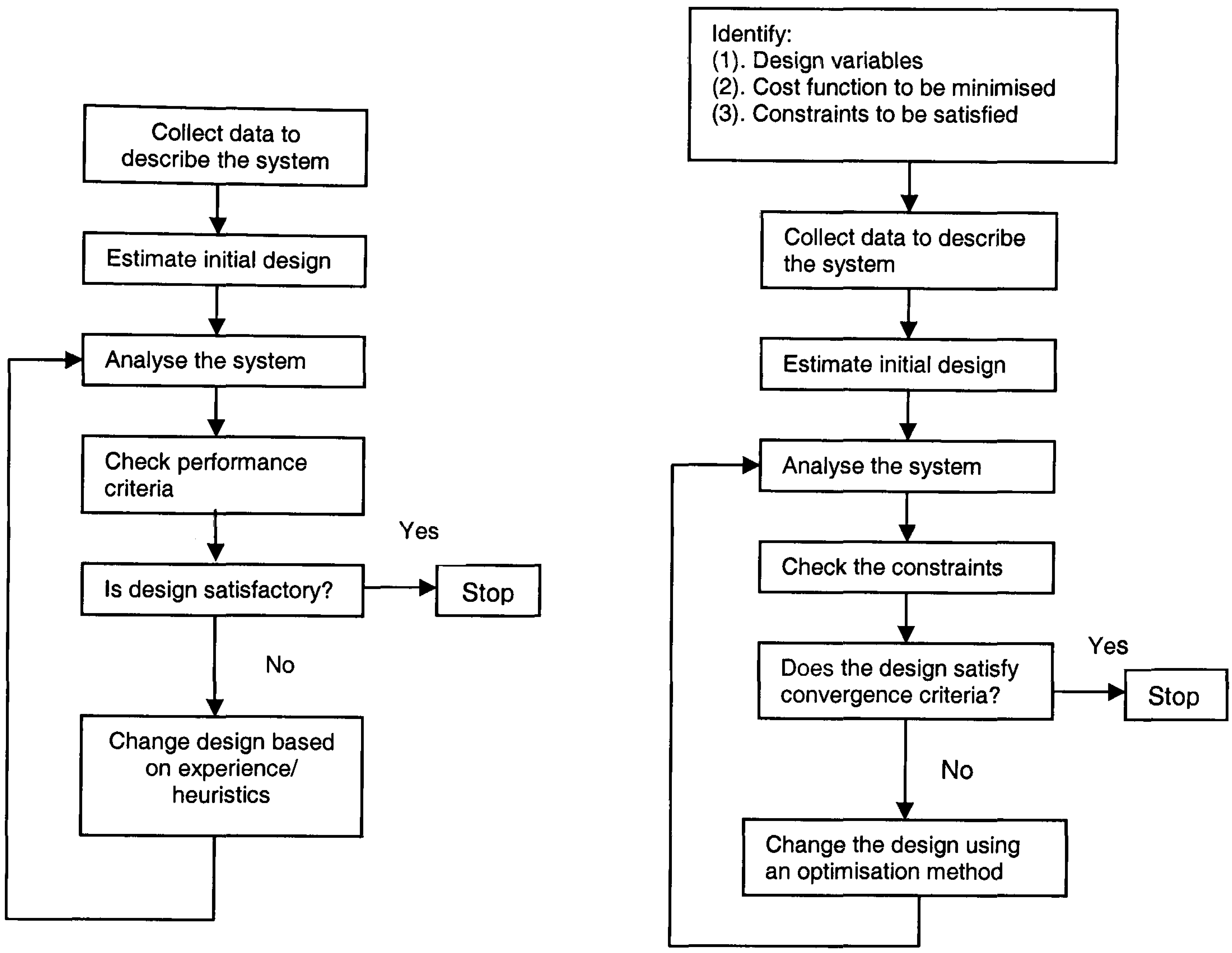
Arora (1989) points out that conventional design processes rely heavily on the designer's or engineer's intuition, experience and skill. This can be a huge limitation when considering detailed designs for modern products or workplaces that are rather complex and have a large number of variables to consider. Together with this, when market conditions and scarcity of materials in the today's competitive world are considered, the conventional method of generating a detailed design becomes rather complex.

To counter this effect and to design better products considering all these variables and limitations, computer aided design methods and optimum design methods have evolved. However, it must be kept in mind that designing is a creative process and especially at the beginning of the process when a preliminary design is decided on, the involvement and the intuition of the designer is invaluable and cannot be replaced.

When the detailed design is considered however, optimum design methods become invaluable in their ability to consider several design variables and constraints that must be satisfied. In contrast to the conventional design process, an optimum design process finds the best possible design in less time due to the better formulation of the design problem. Figure 4.2 illustrates conventional design process and optimum design process as described by Arora.

The 'cost function' referred to in Figure 4.2 (a) is a scalar function that is used as a criterion to compare various designs in order to find the optimum design. This function is also called an objective function and it has to be a function of design variables for it to have an effect on the design. When optimising the design, this function will be either minimised or maximised depending on the criteria. For example, these objective functions can be minimisation of cost, maximisation of profit, minimisation of weight, minimisation of energy expenditure or maximisation of user accommodation. There may be one or several objective functions for an optimisation problem.

For some problems, it is easy to identify this objective function and how it relates to the design variables but for others it requires a considerable degree of insight and experience. This is especially true for complex problems containing a large number of design variables. For example it is hard to identify an objective function for the optimisation of an aeroplane. In such cases the whole problem is divided in to smaller problems, each of which can be formulated as a separate optimum design problem. By defining the constraints or rules that relate these smaller problems with each other they can be linked together to form the whole system.



(a). Conventional Design Process (b). Optimum Design Process

Figure 4.2 - Design Processes (Arora, 1989)

4.4 User-Centred Optimum Design Process for Inclusive Design

A user-centred optimum design process for Inclusive Design is the method developed in this research in order to find better solutions to design problems to maximise the user accommodation. This process has been developed from the above mentioned optimum design process.

The optimum design process is carried out in order to find the best solution to satisfy the original need, within the available means. Although this process considers many aspects of the design one important aspect lacking in it can be the human factor. Although there are some design processes that use user-centred methods currently there is no method that considers individual people and the impact of their characteristics in the process of designing. The design process discussed in this thesis will demonstrate a method of incorporating the often difficult to account for, human factor.

User-centred design, just like any other design approach starts when there is a need for a new product or a system. Then the designer or the engineer decides on the preliminary design. When deciding this, rather than just using the experience, intuition and skill of the designer, abilities and disabilities of the users are also considered. For example, if there are older or disabled users, a ramp maybe used for access to a building rather than steps. Together with other constraints, the design has to satisfy constraints imposed by these characteristics of the individual user. To attain the concept of Inclusive Design, all the users or at least a maximum number of the users must be able to use the product or the system without compromising its cost effectiveness, reliability, durability or efficiency.

Incorporation of this human factor in the design process is often difficult, mainly because it is difficult to express it in terms of design variables. In this research a method has been created to include the physical characteristics of the users in mathematical functions in terms of the design variables. The other difficulties are collecting information needed for design optimisation with regard to the users and the vast number of variables associated with individual users and using these data in design. To overcome these difficulties it is proposed that ergonomics analysis tools are to be used together with multivariate databases of individuals.

The constraints of the users, that is, their abilities and disabilities, joint constraints and their physical dimensions are incorporated in the results of the ergonomics analysis of the preliminary design. Then these results are used as an objective function to be satisfied in the optimisation process. For example, if a particular object cannot be reached by a certain percentage of the users, by varying the position of this object an 'out of reach' value is found for each user. Then expressions for 'out of reach' are written in terms of design variables for each user. Since this 'out of reach' distance depends on the above-mentioned physical aspects of the user, a function written for these 'out of reach' values will be a function of the user's physical aspects as well as the positional variables of the object. Each of these expressions is then used in the optimisation process as objective functions that have to be satisfied. These can also be found for fit and vision or any other design criteria. These objective functions are termed user-related objective functions (UOF)

4.5 A General Mathematical Model for User-Centred Optimum Design

A user-centred design optimisation model can be defined as follows. This has been adopted by the author to include the aspects of the users, from an optimum design model presented by Arora (Arora, 1989):

If design variables are defined as a *n* vector,

$$x = (x_{1,} x_2, ..., x_n)$$

The objective function of the design that has to be minimised is,

$$f(x) = f(x_1, x_2, ..., x_n)$$

If the number of users is p, and the number of different criteria is *a*, user-related objective functions (UOF) are defined as;

$$r_{ik}(x) \equiv r_{ik}(x_{1,} x_{2,} ...., x_n) \qquad \text{where } i = 1 \text{ to } p \text{ and } k = 1 \text{ to } a$$

That is for each user there is one UOF per object. For these users to be able to use the design each of these UOF has to be made equal to zero.

These two sets of objective functions have to be minimised subject to the following constraints.

If the number of constraints is *q*;

$$h_j(x) \equiv h_j(x_1, x_{2,} ...., x_n) \leq 0 \quad \text{where j = 1 to } q$$

These constraints can be either equality constraints, in which case $h_j(x) = 0$ or inequality constraints, in which case $h_j(x) \leq 0$ or some of them can be equality constraints and some are inequality constraints. However, the number of equality constraints should be less than or equal to the number of variables. That is $q \leq n$. If $q > n$ this means that there are redundant equality constraints which are linearly dependent on each other or that there is an error in the formulation.

Functions $f(x)$ and $h_j(x)$ can be linear or non-linear equations but because of the nature of the problems and the method of generating the equations, functions $r_{ik}(x)$ are usually non-linear making the whole problem a non-linear problem. All these functions have to be functions of some or all of the design variables. If they are not, they do not affect the design and hence can be ignored. The general nature of this model allows it to be applied to any type of design problem.

Solving this optimisation model finds solutions to the variables vector $x = (x_{1,} x_2, \ldots, x_n)$. These will then be the new parameters of the design that maximises the user accommodation.

4.5.1 Design Variables

These are a set of variables that define the product or the system. By specifying different numerical values for these, alternate designs can be obtained. The designer has to give careful consideration when selecting these variables because ultimately they determine the values of a product or system. The variables that are used in the optimisation process must be carefully chosen to represent only those properties that need to be optimised.

They can be dimensions of the product or the workplace, parameters concerning the position of objects within the design or they can be both. For example if the workplace is being assembled with existing objects like a kitchen being assembled with cookers, washing machine, refrigerator, shelves etc. the design variables would include the positional variables of these objects. On the other hand, if the design is a design of a pressure vessel, the design variables might be its dimensions such as diameter, height and thickness.

4.5.2 Objective Functions

As mentioned earlier, objective functions are functions that are minimised or maximised to find an optimum design. These are used to find the parameters or dimensions of the optimum design. There can be more than one objective function for a design. The designer's skill and experience has a role to play in formulation of objective functions because a proper understanding of the design problem is imperative at this stage.

4.5.3 User- Related Objective Functions (UOF)

These are the functions that incorporate the user in the optimum design problem. Users of a design are the most important aspect. It is for them that the product or the workplace is being designed. Therefore the designer or the engineer has to ensure that those people are able to use it. If designers are to follow the Inclusive Design concept, they must ensure that all the individuals in the user population are able to use the design or at least to maximise the user accommodation.

The other important thing to remember is that designers can change hardly anything about the users. They cannot change users' abilities or their physical dimensions, their right or left handedness or even their preferences over shape, size etc of products, although may be they can influence this aspect to a certain degree. Therefore what designers can do is to take all the users as they are, and account for each of these aspects when formulating the problem.

To achieve this enormous task of including all users in the design, it is necessary to include all the ergonomics aspects of individual users in these user related objective functions in terms of design variables. Each individual has to be accounted for in the optimisation problem so that the design parameters that can accommodate all or almost all individuals can be found.

Considering the hundreds of users in a user population and the large number of design variables in complex designs and also the various constraints associated with everything, it is apparent that this is not a task that can be done manually. Finding a relationship between the users and the design variables can be done by using ergonomics software. For this an initial computer generated model of the product or the workplace is necessary.

Figure 4.3 demonstrates a modified version of the optimum design process in Figure 4.2 (b). Modifications were done in order to incorporate the users and they are basically the ergonomic analysis of the system and the addition of the user related functions. These user-related objective functions (UOF) are added only if the design fails to achieve the required percentage of user accommodation or if the position of that object affects the position of another, which is used in the optimisation process. When the design fails to accommodate the required percentage of the users, the component of the design that failed this task criterion is identified. Then a 'failure value', for example, 'out of reach' distance for reach criterion, is found for each user by varying its parameters.

The expressions fitted to these separate sets of data for each user are the user related objective functions that have to be satisfied at the optimisation stage. Basically, they are expressions for the 'failure value' in terms of design variables. 'Failure value' gives a numerical value for the failure as in 'out of reach distance'. This value and hence the expression has to be zero in order for that user to be able to perform the task on that particular object. For example, 'out of reach' value has to be zero for a user to reach an object, hence the function representing it should be made equal to zero.

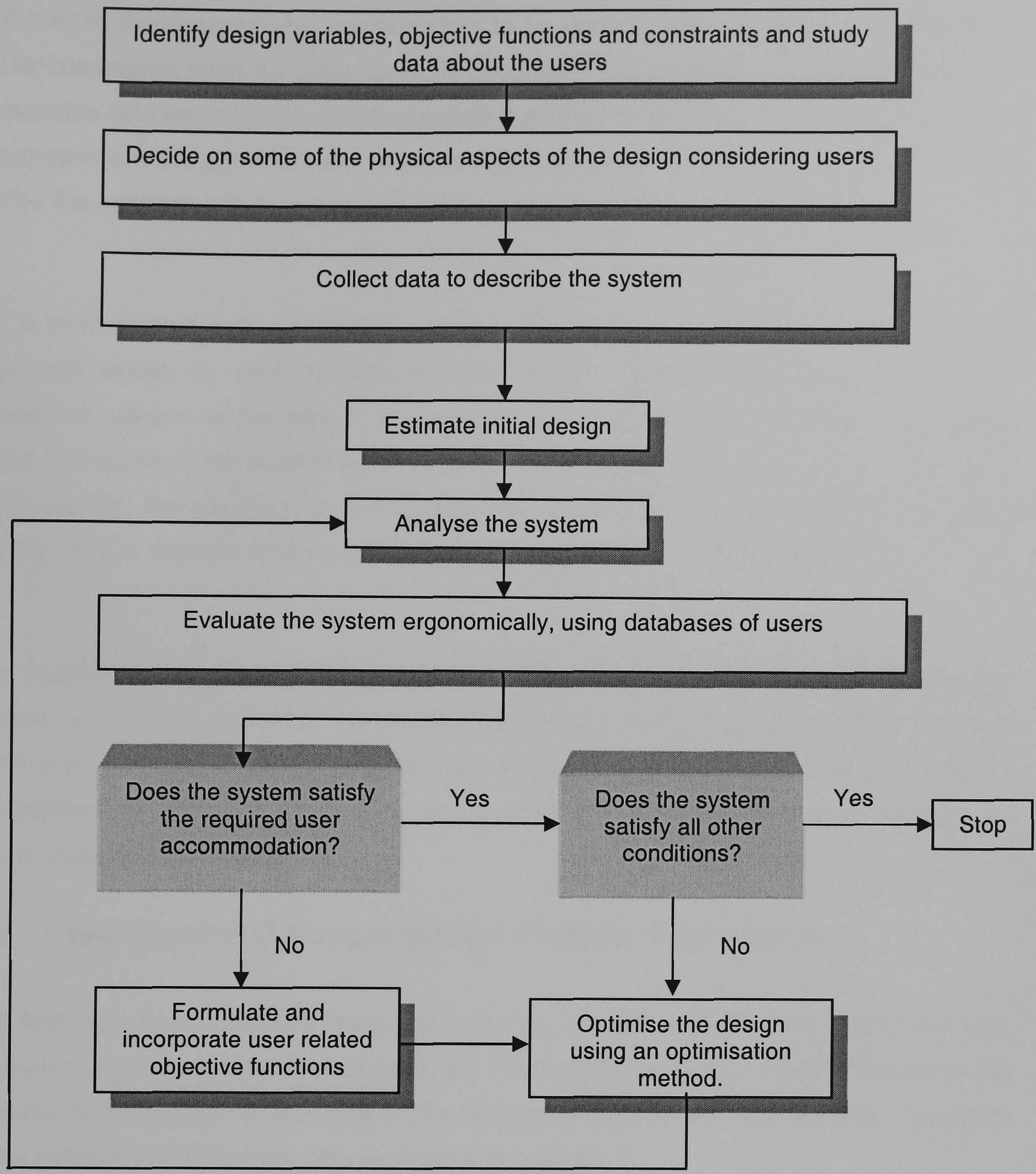


Figure 4.3 - User Centred Optimum Design Process

4.5.4 Constraints

Constraints are the limitations or restrictions imposed on the design. There can be one or several constraints for a particular design. These can be equality constraints, in which case the constraint function is equal to zero or inequality functions in which case the constraint function can be either greater than or equal to zero or less than or equal to zero or it can be a function in between two values. Constraints can be either linear or non-linear functions. In any case, constraint functions must be functions that depend on one or more of the design variables.

Constraints define a unique design solution or a set of acceptable solutions for a design problem by constraining the values of the variables. The identification of the constraints that lead to these acceptable solutions has to be done by the designer. The selection of these constraints must be done carefully because if the problem is over constrained an acceptable solution may not exist that satisfies all the constraints. On the other hand if the constraints are too general there may too many solutions to the problem and these may not be the optimum solution.

For a user-centred optimum design process, the designer has to specify minimum and maximum values for each variable of every object. Together with this in those cases where the position or the size of one object affects another, the constraints that define these limitations to the movement or size have to be specified. Where these constraints might conflict, the designer has the freedom to decide which constraints are to be given priority. This is done by assigning weighting factors to the constraint functions.

Any number of constraint functions can be assigned to the variables provided that the number of equality constraints are less than or equal to the number of variables. Here it is often wise to check these constraint functions again to see if there is any error in the formulation of the design problem, because an error in the constraint functions will give totally unacceptable results.

4.6 User-Centred Optimum Design Problem Formulation

The first step in user-centred design is acquiring a good understanding about the user population and users' functional capabilities. This knowledge can be used to decide on the features of the product or workplace. The designer then needs to identify which tasks the users will perform while using the workplace or product.

Usually the design project is a complex interdisciplinary problem involving numerous components. Most of the time, solving the whole problem as a single unit is impossible. Hence the total problem is broken down into smaller manageable sub problems. This is done by considering the individual components of the product or the workplace being designed. For example, in an automated teller (ATM) machine, these components are the card slot, the screen, the receipt dispenser etc. In a kitchen workplace these could be the cooker, the work surface, shelves etc. In this case if the remodelling of the cooker is allowed, (that is, if the cooker is not a standardised model used in the workplace) its components like the oven, hobs, knobs and the grill are analysed separately. These components can be independent or dependent based on whether remodelling or repositioning it would affect any other component. If there are components that affect others they are all taken together later in the optimisation process.

Then the variables of the system are identified. These variables must be selected so that by changing them alternate designs can be obtained. The problem formulation depends on the selected variables. These can be the physical dimensions of the product or positional variables of the components of the system. The selected variables should be free variables. That is, the designer should be able to assign any numerical value to them. If the assigned values satisfy all the constraints, then the design is usable. The number of design variables identified will determine the flexibility of the design problem formulation. The larger the number of variables, the more flexible the design problem will become. However, this will make the design more difficult to optimise because of the large number of variables. Therefore a balance must be found based on the designers need to have a very flexible design or the ease of optimisation.

The next step is formulating objective functions for these sub problems. These objective functions can take various forms such as minimise cost, maximise ride quality of a car, maximise profit or minimise weight etc. The responsibility lies with the designer or the engineer to select the most suitable objective function or functions for that particular problem. These objective functions must depend on the design variables.

The constraints of the sub problems are identified next. These can be constraints based on size or position. If any of these components affect any other in the system, constraint functions must be found that bind them together to form the composite problem. Again, constraint functions must be functions of design variables for them to have an effect on the design.

The next step is determining the user related objective functions. For this, each of these components is first ergonomically tested using the multivariate data of individuals based on predetermined task criteria. Then for the users who fail this, a 'failure value' is found by assigning various values for the design variables. Each user will have one function for this 'failure value' per component and for them to be able to perform the task that function should be made equal to zero.

All these functions are then formulated into the mathematical model defined earlier in this chapter. This optimisation model is then used in a optimisation software to find optimum values for the variables within the given constraints.

4.7 The User and the Optimum Design Process

To develop an inclusive design approach, it is essential to include users in the design process of a product or a workplace that they are expected to use. Since users are not an integral part of the design, they cannot be directly incorporated. Users' physical dimensions and physical capabilities cannot be directly expressed in terms of design variables to enable them to be used in the optimisation problem. The only way to include the users in the optimisation problem is to evaluate the design ergonomically and find areas where users fail to perform required tasks. The measure of success of the system can be taken as ' how many users failed to perform any of the tasks and hence are being excluded from using the system?' For the system to be truly inclusive, the answer to above question should be 'none'.

4.7.1 Task Analysis

The ergonomic evaluation of the product or system is carried out by modelling it and using a database of individual users. To evaluate the model, it is necessary to identify the tasks that the users will perform when they use the product or the system. The usability of a product is determined by the users' ability to perform specified tasks when using the system. Therefore it is necessary to analyse these tasks based on the abilities of the users to gain an understanding of the successful task performance or to identify the weaknesses in the design if users failed to perform tasks.

These tasks are dynamic processes carried over a period of time. The task analysis is based on key frames or static snap shots of these dynamic processes. Tasks are combinations of task elements such as the user's posture, the environment, duration and repetition. Within the key frames, the posture of the human model is analysed by studying the mechanisms of achieving it (Marshall, 2000). These mechanisms include vision, reach, attitude, posture, position and orientation of the human. Vision consists of position of head, neck and eyes in order to view the target and reach consists of position of hand, forearm and upper arm to reach.

A task is defined by outlining a set of posture mechanisms and specifying task parameters for a known or modelled environment. The task parameters include duration, that is, how long the task is to be performed for and repetition or the number of times the task is to be performed. The percentage of the task element success value that can be considered as a success in other words the tolerance of the task is also considered. For example, if the reachable distance is 400mm, a tolerance of 10% means that a reachable distance up to 440mm is also acceptable.

These tasks are then evaluated using the data regarding the users to identify the successful design elements and also the design elements that failed the task analysis.

4.8 Generation of User-related Objective Functions

The main objective of formulating UOFs is to provide a method to enable the physical characteristics of the users to be applied in the optimisation process. As mentioned earlier the process of generating these UOFs has to consider the physical aspects of the users as well as the variables of the design.

The consideration of the physical aspects of the individual users is done by utilising a computer model of each individual. This model of the individual represents the real person by their physical dimensions, somatotype (flesh shape), joint constraints, other abilities and disabilities including vision. Cognitive capabilities and the strength of individuals should also be considered but they are beyond the scope of this research. Using these models and predetermined task criteria, all the objects in the workplace that need to be optimised are evaluated.

If an individual fails on one or more of these tasks, the 'failure values', for that component for all the users is found by varying the variable parameters of that component. A 'failure value' gives a quantitative value for the failure, which is obtained with respect to a certain position or a dimension of the object.

By varying the variable parameters of an object different values for these 'failure values' are obtained for different positions or dimensions for each user. These parameters are the design variables of that particular object and each object may have one or several variables depending on its physical characteristics and its degrees of freedom of movement. For example, if only the positional movements of the components are considered and not their size, the shelves of a kitchen or a supermarket etc have only one degree of freedom, in the vertical direction. But a kettle on a work surface has three degrees of freedom in x, y directions across the surface and the rotation around the vertical axis. Since it depends on all these variables, the out of reach value is a function of all these variables.

The set of values that are obtained for each user in this method can be described as follows. If 'failure values' are denoted by v_j and positional variables of the component are denoted by x, y, z, α, β and θ where x, y, z are the values in x, y and z directions and α, β and θ are rotational variables, then what we obtain from this analysis is a discrete data set that has the form;

$$user_i \Rightarrow (x_1, y_1, z_{1,}\alpha_{1,}\beta_1, \theta_1, v_1), (x_2, y_2, z_{2,}\alpha_{2,}\beta_2, \theta_2, v_2), \ldots, (x_n, y_n, z_{n,}\alpha_{n,}\beta_n, \theta_n, v_n)$$

where $i = 1$ to m

Mapping a formula for these 'failure values' against the variables will result in a function of those variables. These are the functions that are termed user-related objective functions (UOF).

For example for a reach criterion, the UOF of a user for a certain object will be

f (design variables) = 'out of reach' distance

Since the models represent all the necessary physical aspects of the individual, it can be safely assumed that the resulting UOFs also represent these user aspects. These sets of data are found for each user per object in order to get UOFs for all the users.

The next step is to fit functions to these discrete data sets. The fact that these data were obtained experimentally for a real life problem and do not follow a known rule makes it difficult to find expressions. Another aspect of these data is that they can be independent or dependent of each other. A trial and error method was used to find what kind of a function would fit them. The variables have non-linear characteristics. Hence non-linear functions are fitted using the least squares method.

The least squares method is finding the polynomial that minimises the sum of the squares of the deviations. Papalambros (Papalambros, 1988) shows that the normal equations that are used to find the coefficients of the polynomial for least squares fit of an nth degree polynomial using m data points are

$$\begin{pmatrix} m & \sum x_i & \sum x_i^2 & \cdots & \sum x_i^m \\ \sum x_i & \sum x_i^2 & \sum x_i^3 & \cdots & \sum x_i^{m+1} \\ \vdots & \vdots & \vdots & & \vdots \\ \sum x_i^m & \sum x_i^{m+1} & \sum x_i^{m+2} & \cdots & \sum x_i^{2m} \end{pmatrix} \begin{pmatrix} a_0 \\ a_1 \\ \vdots \\ a_n \end{pmatrix} = \begin{pmatrix} \sum y_i \\ \sum x_i y_i \\ \vdots \\ \sum x_i^m y_i \end{pmatrix}$$

This must be solved simultaneously to obtain a_0, a_1, ..., a_n. This can be extended to polynomials with several variables. However since this is difficult to solve manually a computer system is used to fit functions to these data points to obtain UOFs.

For example, when considering only x, y and z parameters the best-fit function found through trial and error by using the computer software was of the form:

$$a + bx + cy + dz + ex^2y + fxy^2 + gx^2z + hxz^2 + jxy + ixz + kyz + lxyz + mx^2yz + nxyz^2 + px^2y^2z^2$$

Coefficients *a, b, c, d, e, f, g, h, i, j, k, l, p* were then found considering the data sets obtained for each user. Then these UOFs are used in the optimisation process.

4.9 The Complexity of User-Centred Optimum Design problems

The simplest user-centred optimum design problem is the product or workplace that has only one object with only the positional variables. This problem can be solved with just one set of UOFs and simple constraint functions. With each added object and added variable the complexity of the problem increases. However if these objects do not relate to each other, i.e. the positions or sizes of an object does not affect any other object, then they can be treated as separate objects.

The most complex user-centred optimum design problems are those that have several objects with positional and dimensional variables that relate to each other. For example in a kitchen workplace, the height of the cooker has to be the same as the height of the work surface and the sink. The size of the sink must be considered with respect to the position of the tap etc. In this respect these entire objects are interdependent on each other.

The evaluation of these workplaces will be an enormous task with a large number of task elements each of which needs to be analysed separately. The task structure for these design problems has to be built by analysing all the individuals and their interaction with every object. The task criteria, which are reach, fit and vision have to be utilised in each task element analysis. As the number of objects in a workplace increases, the importance of evaluation of fit also increases.

The resulting constraint model will have a huge number of UOFs and objective functions. In addition there will be a large number of constraint functions, which will also be complex in order to accommodate all the constraint relationships. The designer has to be vigilant in these cases because there may be too many constraints and it will be hard to find a solution within these constraints. If this happens, the designer can relax a few chosen constraints.

4.10 Summary

In this chapter, the method developed in this research to tackle the Inclusive Design problem is presented. In the Inclusive Design the main aim is to include all the intended users or at least to maximise the user accommodation of a product or a workplace. To achieve this, the proposed method utilises an optimisation technique with unique objective functions that represent the capabilities of each individual user. A mathematical model for this optimisation problem is presented together with the method of generating UOFs.

The next chapter deals with the software developed by using the above-mentioned theoretical aspects.

Chapter 5

Software Design and Modelling

5.1 Chapter Overview

This chapter will introduce the new software SHIELDS that has been developed to utilise the methodology described in chapter 4, and its components. The basic software architecture of SHIELDS is shown and analysed. Each of the three items of software that is used in SHIELDS is described and how it is used in the optimisation process is explained. Various aspects of these three pieces of software and how they are linked together are also described. The use of the HADRIAN evaluation and how MATHEMATICA was used to fit functions to HADRIAN output data is discussed in detail. This chapter also shows how SWORDS macros were written and used in the optimisation process. Finally it provides a description of the user interface of SHIELDS and how to use it for the optimisation of designs considering users.

5.2 Introduction

The prediction of the percentage of users physically accommodated in a design is of utmost importance to the inclusive design approach. At the same time, if the parameters of the product or environment that maximise the user accommodation can be found without going through tedious user trials and laborious programming to test each individual, it would result in a huge saving financially and with respect to manpower. The software SHIELDS (System for Human Interaction Evaluation and Design Synthesis) was created with the intention of providing the designer with the capability of finding the user accommodation and also to enable the designer to find the parameters of the product or workplace under consideration that would maximise this. SHIELDS allows the designer to model the product or the workplace and evaluate it ergonomically. It contains a database of people, which can be used to generate computer based human models to be used in these evaluations. The most important capability of SHIELDS is its ability to predict the design parameters that maximise user accommodation.

As shown in Figure 5.1 SHIELDS is essentially a combination of three pieces of software bound together by the underlying Visual Basic code. The communication between these pieces of software is done through a series of text files. Outputs of one software are the inputs to the other and macros specific to each of the software are used to manipulate these inputs to get the desired output. Each of these pieces of software is very different to the other two, making the combining process rather cumbersome.

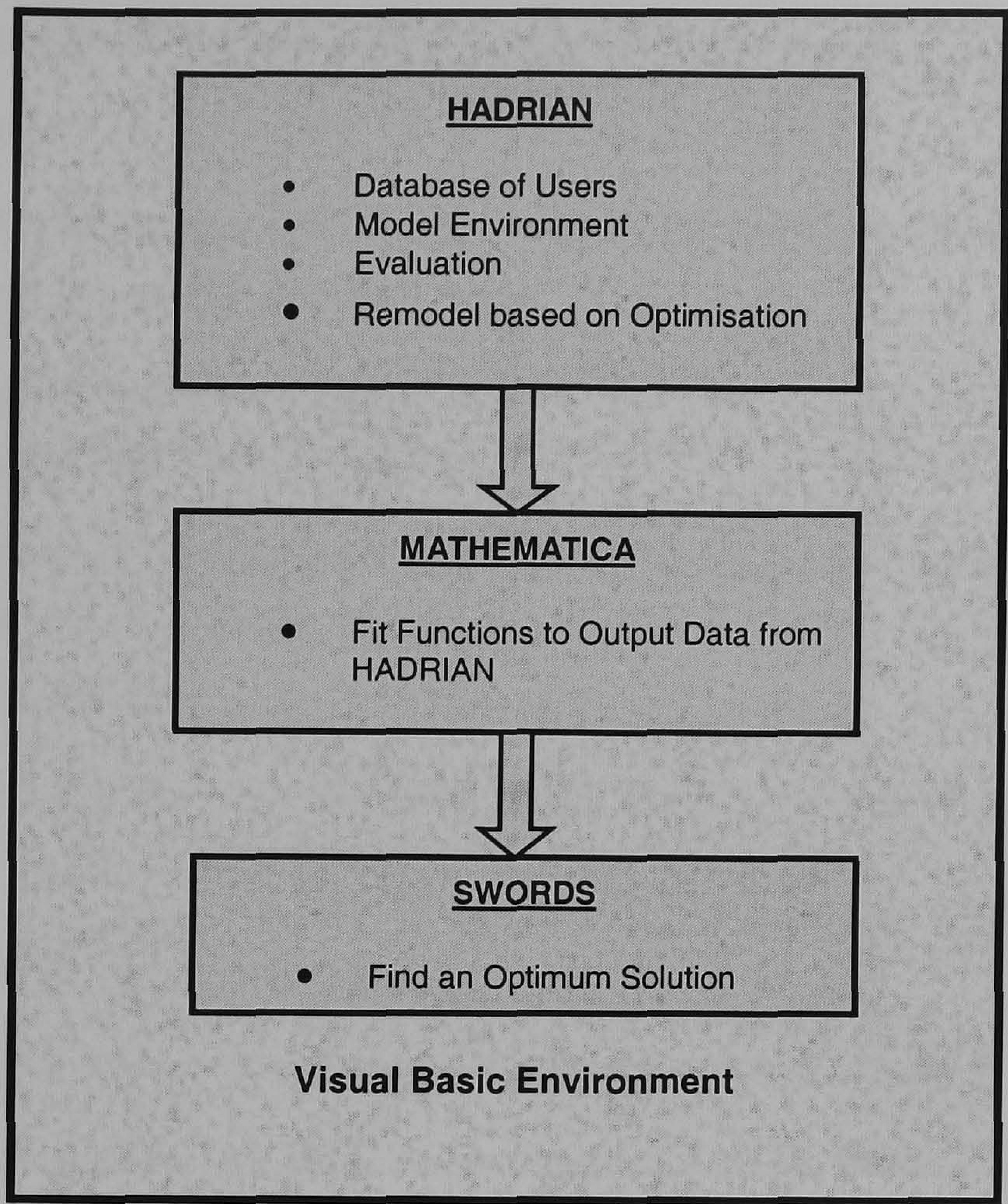


Figure 5.1 - The Components of SHIELDS

For example, HADRIAN is the ergonomic analysis software used in the system while MATHEMATICA provides the formulation of mathematical equations. SWORDS allows the optimisation process to be carried out regarding constraints and objective functions. All of these work together to provide the optimisation of products and workplaces considering the often difficult to account for, human factor.

5.3 Methodology

In developing the software SHIELDS the following software development life cycle method adopted from Bennet (Bennet, 1999) was followed approximately.

5.3.1 Requirements Analysis

Requirements

- Ability to read CAD generated computer models of products or workplaces

- Ability to perform ergonomics evaluations based on individual user data
- Ability to formulate design problems using individual user characteristics, physical aspects of the design and the constraints into mathematical optimisation models
- Ability to optimise the formulated model and output results

Available resources

- SAMMIE/HADRIAN model building and ergonomics evaluation software that also contain data regarding individual users
- Mathematical software called MATHEMATICA that is able to fit functions to data that has more than three variables
- SWORDS constraint modeller that has the ability to find optimum solutions to a large number of variables considering a large number of objective functions and constraint functions
- Visual Basic software to formulate bridges between these software

Characteristics of the users of the software

- They will be product designers, product developers or engineers
- They will have a knowledge of how to create CAD models of the product or workplace
- They will have knowledge of how to formulate constraints functions of the physical limitations of the CAD model
- They need not have extensive knowledge of ergonomics or optimisation models or methods.

5.3.2 Design

Input and output design

- The system needs three forms of input. First, the input regarding the product or the workplace is given in the form of the CAD model. Second, the data regarding the users can be chosen by the user of the system from the HADRIAN database, which can be accessed within SHIELDS. Third, input regarding the constraints of the product need to be entered by the users of the system.
- Outputs of the system are the new optimised dimensions/positions of the product or workplace and the list of users who are able to use the product at the new positions.

Data storage requirements

- A series of temporary files within the system to store data needed for the evaluation and calculation purposes.

Process design

- Design and construction of HADRIAN analysis
- Development of MATHEMATICA notebooks for function fitting
- SWORDS optimisation and development of macros
- Integration of all the above factors within one system

These are described in the following sections.

5.3.3 Implementation

Implementation of the software is carried out mainly by using a Visual Basic environment as described in detail later in the chapter.

5.3.4 Testing

The software SHIELDS was tested while in construction and afterwards by testing each programme separately and also with 'dry running' the total system with a simple model.

5.3.5 Maintenance and retirement

These phases of the software life cycle were not considered in this software development.

5.4 The Software System Design

The SHIELDS system was designed to accomplish the requirements specified in section 5.3.1 using the available resources. The components of SHIELDS and the inputs required by them in order to get the output required are illustrated below in Figure 5.2, Figure 5.3 and Figure 5.4.

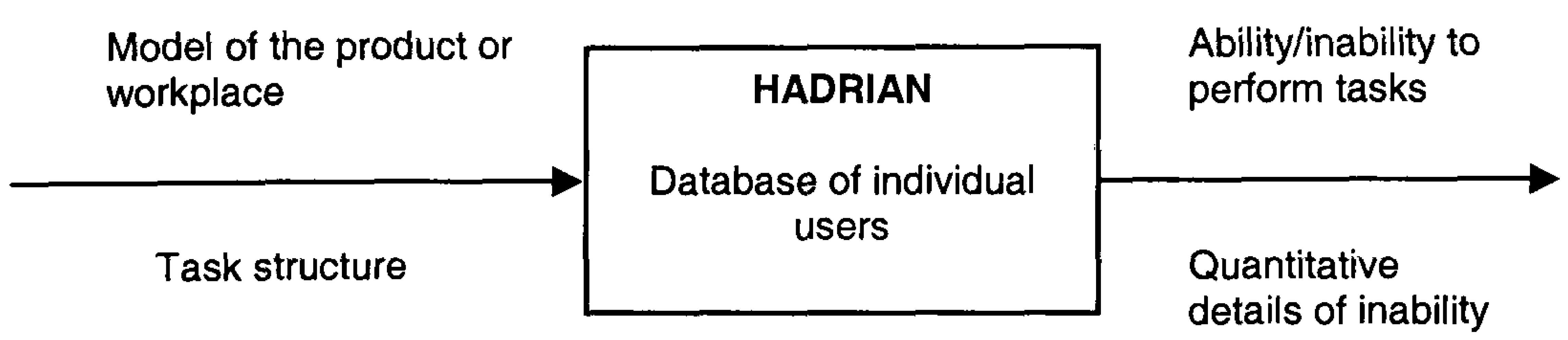


Figure 5.2 - Inputs and Outputs of HADRIAN

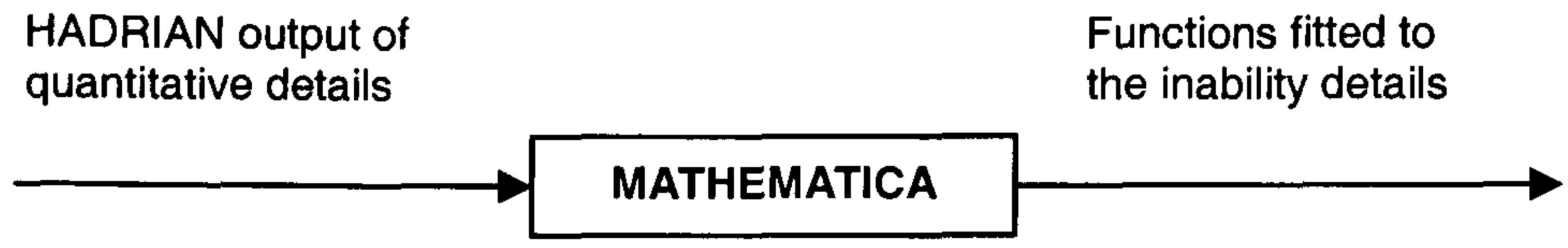


Figure 5.3 - Inputs and Outputs of MATHEMATICA

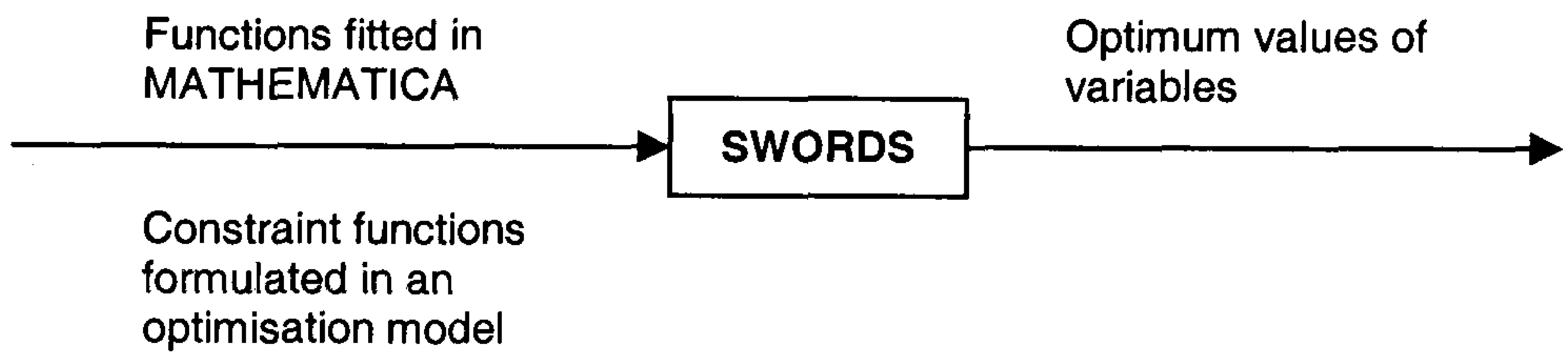


Figure 5.4 - Inputs and Outputs of SWORDS

Methods of entering these inputs and the processes carried out in order to get the desired output are programmed in SHIELDS.

5.4.1 Ergonomics Analysis

The SHIELDS software system uses the software HADRIAN for its ergonomics analysis in order to obtain the ability and inability of users of products to perform the tasks specified. Out of all the ergonomics software available, only HADRIAN contains a database of individual users. Together with this, it also allows the three-dimensional model building facility and evaluation of it using the human models generated using the database.

The important aspects of using HADRIAN are:

- HADRIAN contains the ability to evaluate models of the product or workplace three dimensionally.
- HADRIAN has a built-in database of individual users.
- HADRIAN can model these individuals, their physical dimensions and joint constraints as 3D human models and use them for the ergonomic evaluation.
- HADRIAN human models can mimic human postures to make the evaluation realistic.
- HADRIAN has the ability to analyse individual tasks and pin-point failure elements.

HADRIAN outputs can be written as text files and it can read text files enabling it to be used in SHIELDS.

5.4.1.1 Model Building

HADRIAN uses SAMMIE's functionality and capabilities in building models of the products or workplaces and in evaluating them. Particularly, a boundary representation method is used to construct its solids, which come in the form of several primitives, for example, cuboid, cone, cylinder, polyprism and module. Users can use these primitives to build their products and workplaces. The SAMMIE modeller uses a hierarchical data structure to specify relationships between objects as illustrated in Figure 5.5. These objects can later be modified as the evaluation progresses.

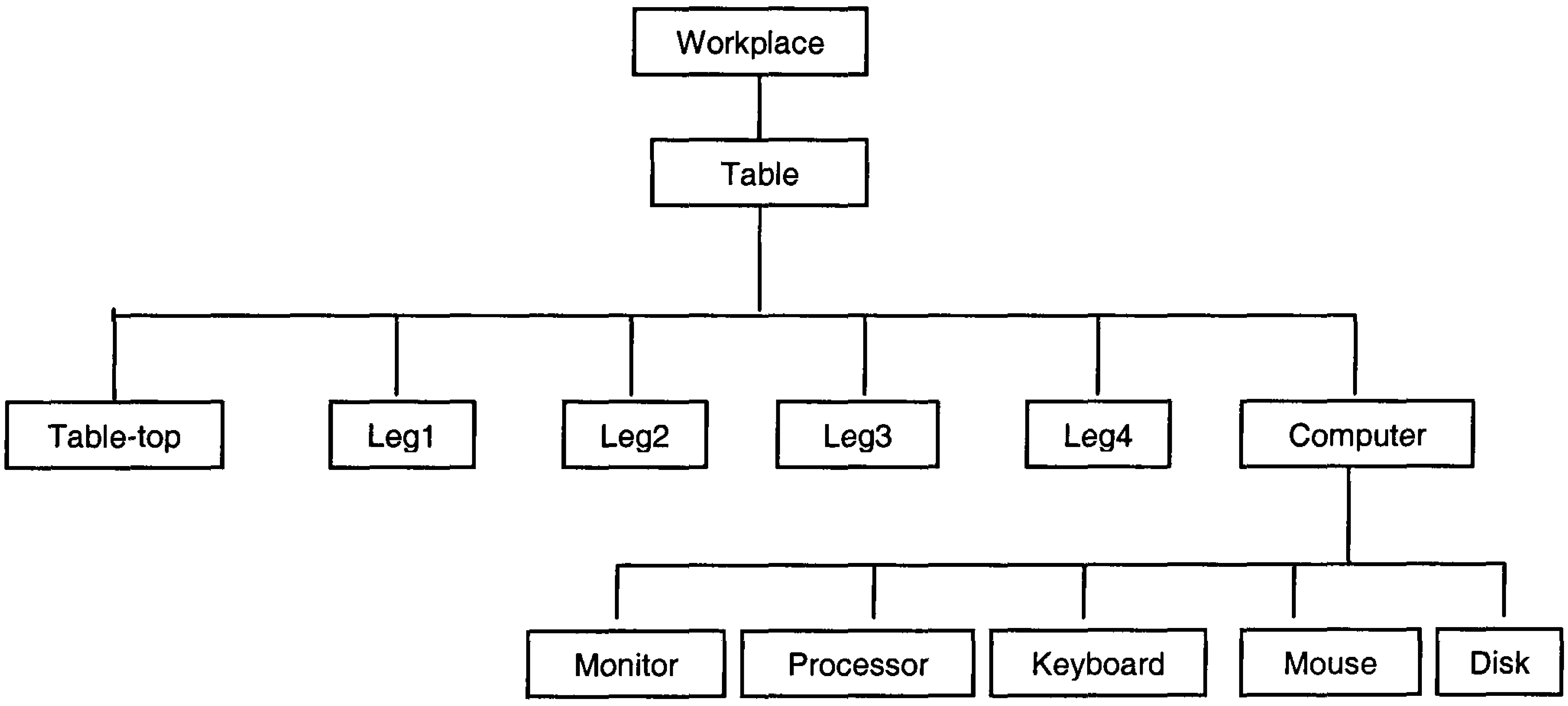


Figure 5.5 - The Data Structure for a table with a computer model attached

HADRIAN models built through SAMMIE can have as much detail as the designer wishes them to have. However for evaluation purposes, the only necessary details are the basic dimensions of the design. By limiting the details to the essentials the designer can save time in the design and evaluation processes. Also it is possible to download or read models made in other CAD software into HADRIAN enabling the designer to use pre-constructed models.

5.4.1.2 Evaluation Process

The model built in HADRIAN is evaluated depending on predetermined task criteria. The designer describes these tasks to the system through a series of user commands. These task commands are an integral part of HADRIAN and they define the individual task elements that make up the overall task. These commands are made up of a key word and a target or value and also a set of optional parameters. For example, to implement the 'vision' task criterion, one of the commands that the designer will use is the 'LOOK' command. Execution of this command prompts the human model to view the specified target. The target is an object or a point in the modelled environment, which has to be specified together with the other parameters.

The human models used for this evaluation were created from the individual users' data in the database. The objects in the model were evaluated for each of these individuals and an output regarding the object that failed and why it failed, for example 'failed because object was out of reach by 10mm', and the user or users who failed it can be obtained from this evaluation.

5.4.1.3 Failed Elements

The objects that failed the task criteria are analysed again for all the users in order to proceed with finding parameters that would be successful in achieving the specified task. To be able to do this, first it is necessary to identify the object and then its 'free' parameters. Free parameters are those that can be changed in the design process. For example, in the ATM machine card slot, the free parameters are its x. y. z co-ordinates if its size was already determined.

Each component of the workplace may have one or several free parameters or in other words, free variables, depending on its degrees of freedom of movement. For example, the shelves of a kitchen or a supermarket etc have only one degree of freedom, in the z direction. But a kettle on a work surface has three degrees of freedom in x, y directions and the rotation around z-axis. By varying the position of the component, out of reach values for each position are recorded for the desired object and for each user, if the criterion is set for reach.

Figure 5.6 shows a sample set of data obtained for a single user (Subject 11) to reach the card slot of an ATM machine. Out of reach values were obtained by varying its position.

Subject 11

REACH Card Slot

x	y	z	Out of reach by
-33.31	696.52	990.25	0.00
-33.31	696.52	1115.25	0.00
-33.31	696.52	1240.25	0.00
-33.31	697.40	1488.13	4.93
154.30	696.55	990.23	0.00
154.26	696.55	1115.23	0.00
153.24	696.55	1240.23	15.96
153.19	696.55	1365.23	0.00
153.12	697.42	1488.11	27.51

Figure 5.6 - A Data Sample obtained for the ATM Card Slot

0.00 indicates that it is within reach for that particular position. All the positive figures for out of reach indicate varying degrees the respective users have in their inability to reach these positions.

taskres - Notepad

File Edit Format Help

```
! HADRIAN generated results file.
!
! ——————————————
! TEST POSITION        1
Subject11
REACH Slot
  -33.31  696.52  990.25   0.00
REACH Keys
 080.91  448.38  657.77   0.00
REACH Dispenser
  82.25  693.40  825.37   0.00
Subject12
REACH Slot
  -33.31  696.52  990.25   3.35
REACH Keys
 080.91  448.38  657.77   93.68
REACH Dispenser
  82.25  693.40  825.37   54.27
Subject27
REACH Slot
  -33.31  696.52  990.25   45.54
REACH Keys
 080.91  448.38  657.77  233.76
REACH Dispenser
  82.25  693.40  825.37  123.30
Subject28
REACH Slot
  -33.31  696.52  990.25   35.72
REACH Keys
 080.91  448.38  657.77  154.50
REACH Dispenser
  82.25  693.40  825.37   94.14
Subject40
REACH Slot
  -33.31  696.52  990.25   0.00
REACH Keys
 080.91  448.38  657.77   0.00
REACH Dispenser
  82.25  693.40  825.37   0.00
Subject41
```

Figure 5.7 - A Part of HADRIAN Generated Output File

These output data are written to a text file to enable them to be used in other software. Part of the actual output file obtained from HADRIAN for three objects in the ATM machine is shown in Figure 5.9. It contains data for several users and objects slot, keys and dispenser. The first three columns are the x, y and z co-ordinates while the fourth column contains the out of reach value for each of those positions.

5.4.2 Function Fitting

In the user-centred optimisation process, the objective functions that accommodate the user are derived from the above data. The initial challenge with this approach was determining how to translate the relevant sets of discrete data into the objective functions that the SWORDS software can understand. The method adopted was to fit functions to these data and use these functions in SWORDS. These functions that were given the name 'user centred objective functions (UOF)', are written for each user for a particular object in order to optimise the user accommodation for that object. Therefore, the data obtained from HADRIAN analysis is categorised based on the user and the object.

Functions were fitted to these data by using the software called MATHEMATICA. This software has the capability to fit linear and non-linear functions to sets of data that have several variables.

The important aspects of using MATHEMATICA are:

- MATHEMATICA has the ability to fit functions into a wide range of data categories.
- MATHEMATICA fits functions to data that has more than 3 variables.
- MATHEMATICA can read and write text files enabling it to be used with other software.
- MATHEMATICA functions and functionality can be accessed externally.

MATHEMATICA has built in functions to fit linear and non-linear functions to data. It finds the least squares fits to these data by taking a list of functions or values specified, and tries to find a linear combination of them, which approximates the data as well as possible (Wolfram, 1999). The accuracy of the fit is measured by the quantity $c^2 = \sum_i |F_i - f_i|^2$, where F_i is the value of the i^{th} data point, and f_i is the value obtained from the fit. The best fit is the one, which minimizes c^2.

As well as being able to use any number of variables in fitting curves, it is possible to fit data into any form of function, using MATHEMATICA. For example, Figure 5.8 illustrates two forms of equations fitted to the same set of data. However, there is no guarantee that these functions are fitted exactly or which one fits better. To find this out, either a trial and error method, or a statistical method has to be used. A trial and error method was used in this study, to find the better-suited curve for the obtained data sets.

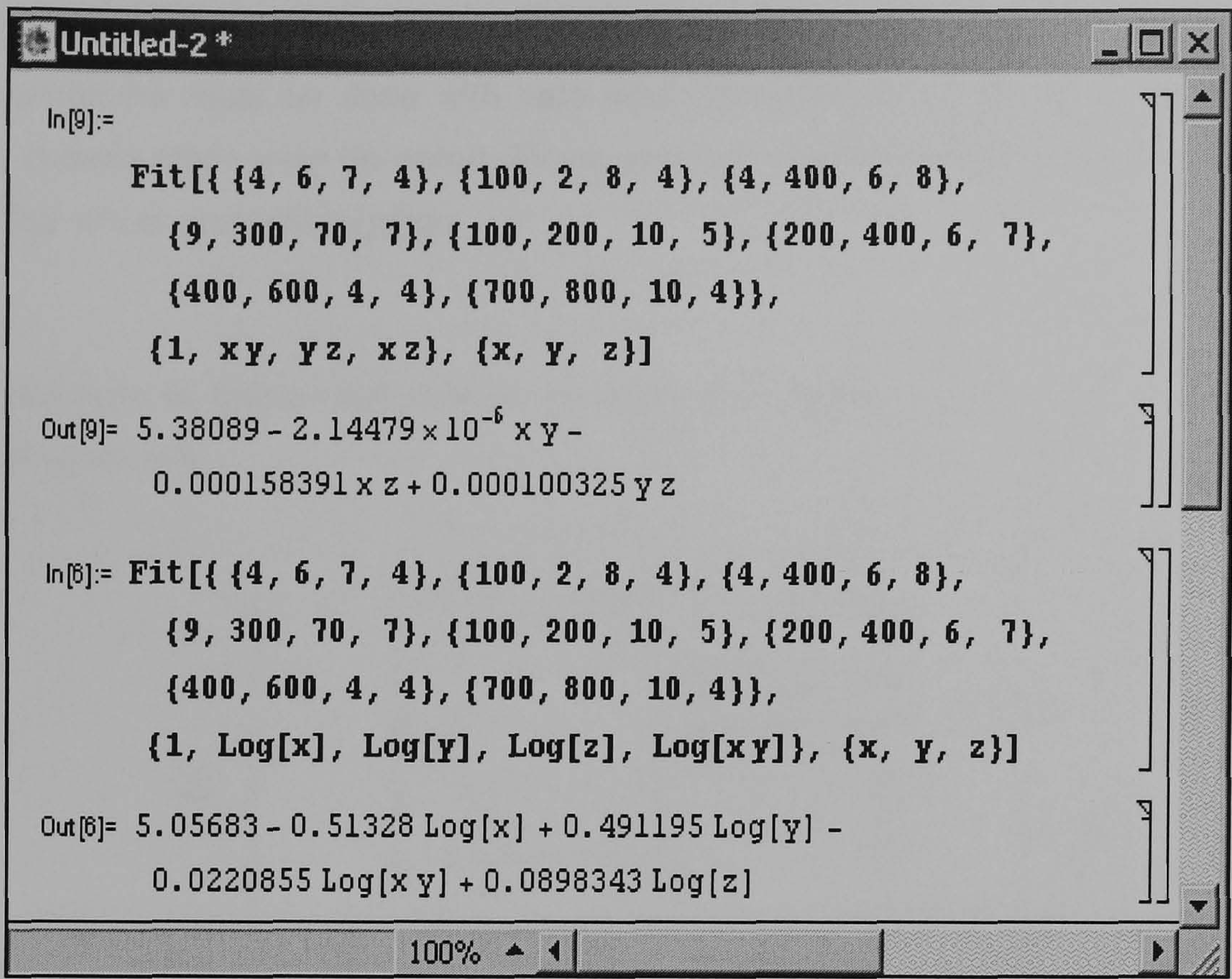


Figure 5.8 - Two different functions fitted to the same set of data

Another important thing with regard to the optimisation is that, if the fitted functions are too sensitive to small changes of their variables, it is difficult to use them in the constraint modeller for the optimisation process. When this happens, the constraint modeller does not find a true optimised position. Whether the fitted curves are too sensitive to small changes of the variables was also found by using trial and error methods.

5.4.3 Optimisation

Optimisation of the design is done by considering the free variables of the design, the user abilities and the constraints that have to be applied in order to achieve a feasible product or a workplace. Variables of the design and most of its constraints have to be decided on by the designer. The objective functions and the constraints are then written as functions of the design variables. SHIELDS gathers UOFs and constraint functions and then formulates the constraint model from them. Then optimum solutions to these functions are found by using the constraint modelling software SWORDS.

Before attempting any optimisation, the design problem must be decomposed into manageable parts. Many design problems, when taken as a whole, are very large and have many variables and their objective functions are not easily established. Hence, considering each of the objects in the design separately enables difficult and large design problems to be formulated for optimisation. Breaking down or decomposition of these design problems must be done with care and the relationships between the separated objects to each other must be noted. These are then used at a later stage of optimisation to bind the whole problem together.

As an example of these relationships between the objects consider the ATM machine shown in figure 6.5.

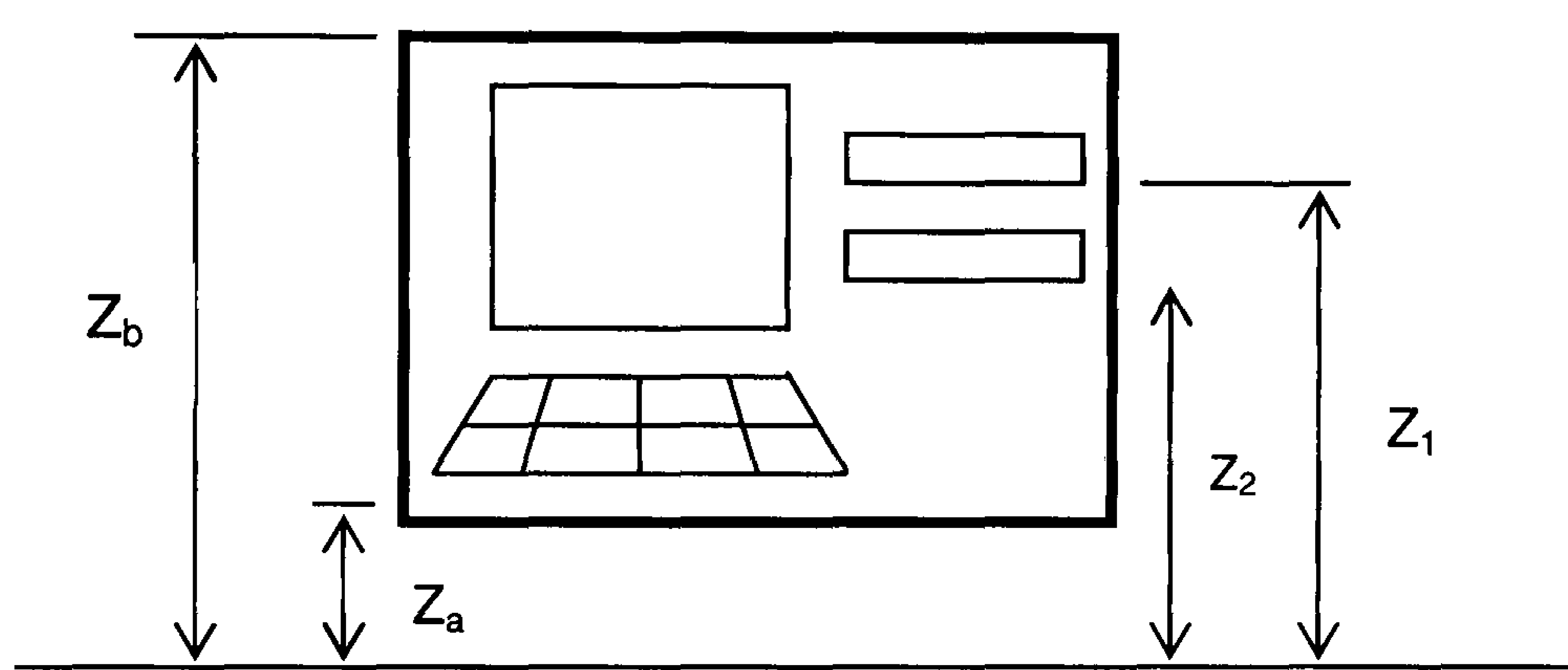


Figure 5.9 - A line diagram to represent the ATM machine

Z_a and Z_b are the minimum and maximum heights of the ATM casing and the card slot and the receipt dispenser are to be placed within this. The difference between Z_a and Z_b is say, 500mm. Together with this, if the distance between the height of the card slot (Z_1) and the height of the receipt dispenser (Z_2), needs to be set at 60mm, these constraint can be defined as,

$$Z_a < Z_1 < Z_b,$$
$$Z_a < Z_2 < Z_b,$$
$$Z_1 - Z_2 = 60,$$
$$Z_b - Z_a = 500$$

After each of the individual objects in the design that need optimisation have been identified, they are subjected to HADRIAN evaluation and functions are fitted to the output data obtained from this analysis using MATHEMATICA. Then these functions must be incorporated in SWORDS macros ready for optimisation. Since the MATHEMATICA output file cannot be written in the exact form needed in SWORDS macros, it is edited using the Visual Basic code.

The important aspects of using SWORDS are:

- SWORDS has the capability of finding an optimum solutions within stated constraints.
- SWORDS can accommodate a large number of variables in its analysis.
- SWORDS is able to read and write text files enabling it to be accessed externally.
- SWORDS has the flexibility of reading different forms of mathematical expressions.

5.4.3.1 Objective functions

The objective functions that can be used in the design optimisation process are two fold. Firstly, they can be the cost functions relating to the product directly as mentioned in chapter 4. Secondly, the objective functions can relate to the users (UOFs), which are generated by MATHEMATICA and written in terms of the free design variables. For the constraint modeller, only one form of objective function i.e. the UOF was defined. The ability to model the other objective functions in it are outside the scope of this research.

5.5 Implementation

The implementation of the software SHIELDS was performed in the following steps.

- Code written in order to achieve the linking between the three components of the software used in SHIELDS.
- Code in MATHEMATICA
- Code written for SWORDS macros

  To read in constraints

  To edit UOFs

  To formulate the optimisation model

  To write the whole macro including all the above

- Code written to obtain the output

Linking between HADRIAN, MATHEMATICA and SWORDS was done through VB code. A huge advantage of using VB programming is its ability to utilise code contained in other applications. Object Linking and Embedding (OLE) technology used in VB allows this facility by enabling the user to employ data and components from one application in another application. A control button called OLE container control can be placed on a VB form and then any object such as a Word document, an Excel spreadsheet or totally different software like SWORDS or HADRIAN can be embedded in or linked to the VB form.

HADRIAN is embedded in the SHIELDS user interface through OLE technology. This was done by using the OLE container control VB form that was used to build the SHIELDS interface. This gives direct access to HADRIAN within SHIELDS, and the SHIELDS user can utilise all the functionality of HADRIAN in the evaluations. The results of HADRIAN evaluations are written automatically into text files.

However, to use the HADRIAN output file in MATHEMATICA, that file has to be edited and this is done using the VB code part of which is shown in Figure 5.10. This code eliminates the text strings from the file while retaining the numeric values.

```
Do While mtext.AtEndOfStream = False
     a = mtext.ReadLine
     If Left(a, 5) = "Subje" Then
     Else:
        If ((Left(a, 5) = "REACH") Or (Left(a, 1) = "!")) Then
         Else:
          a = Trim(a)
          pos1 = InStr(1, a, "   ", vbTextCompare)
          pos2 = InStr(pos1 + 2, a, "  ", vbTextCompare)
          pos3 = InStr(pos2 + 2, a, "  ", vbTextCompare)
                   r = Trim$(Mid$(a, 1, pos1))
          s = Trim$(Mid$(a, pos1, pos2 + 1))
          t = Trim$(Mid$(a, pos2 + 8, pos3 - 4))
          StrOReach = Trim$(Mid$(a, pos3 + 12, Len(a)))
          x = CDbl(r)
          y = CDbl(s)
          z = CDbl(t)
          OReach = CDbl(StrOReach)

          X1 = FormatNumber(x + 1000, 2, vbTrue, vbTrue, vbFalse)
          Y1 = FormatNumber(y + 1000, 2, vbTrue, vbTrue, vbFalse)
          Z1 = FormatNumber(z + 1000, 2, vbTrue, vbTrue, vbFalse)
          OReach = FormatNumber(OReach + 1, 2, vbTrue, vbTrue, vbFalse)
```

Figure 5.10 - A sample of the Visual Basic code that edits HADRIAN output files

The function fitting capability of SHIELDS is accessed just by choosing the number of variables in the HADRIAN output file. This activates the code that chooses the necessary MATHEMATICA notebooks and invokes MATHEMATICA in the background, which accesses the HADRIAN output file and fit functions accordingly.

This edited data is again written into a separate text file that is then accessed by MATHEMATICA. This text file contains only the numerical values of the data in columns but as yet without categorising them according to the user and the object. That is done in MATHEMATICA code in its notebooks. These notebooks are the front end of MATHEMATICA that are used to input data into the system and to get an output. By using Active X software in VB it is also possible to access MATHEMATICA remotely.

Fitting curves in MATHEMATICA is done by specifying the data, the variables and the functions that the data is assumed to follow. For example, generally, curve fitting is specified in the following form:

Fit (*data, funs, vars*)

This function fits a list of data points using the functions *funs* of variables *vars.*

A specific example of this is shown in Figure 5.11

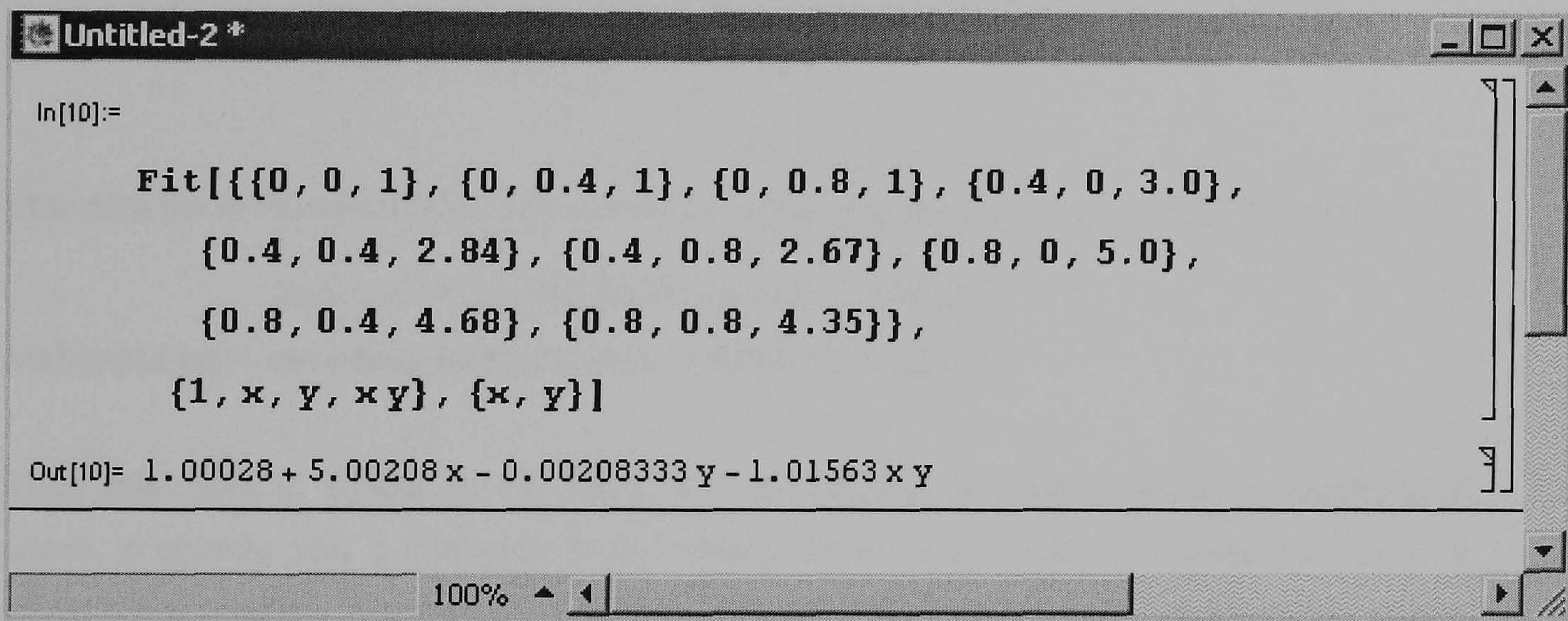


Figure 5.11 - An example of a MATHEMATICA notebook used to fit a function

The first three lines of the notebook show the given data set and the next line shows specified basis functions that the total function is constructed from, and the variables {x, y}. MATHEMATICA has found a fit to these data of the form $a_1 + a_2x + a_3y + a_4xy$. If any of these coefficients are very small we can safely assume them to be zero and that part of the function it is associated with is not a part of the whole function.

Polynomial fits of any degree can be given in this form. However, if there is a reason to believe that the data follows a particular functional form the appropriate functions can be included in the basis functions list given to fit.

The problem with using this method to fit expressions to the data sets obtained from HADRIAN is that, those data do not follow a known pattern because they were obtained experimentally for real life problems. Hence the basis functions that have to be specified to Fit are arbitrary functions. An extensive trial and error method was used to find the best fitted functions. This trial and error method involved linear as well as non-linear functions and formulae that contained exponentials, sine and cosine, logarithms as well as most of the combinations of the variables. In general, if there are n data points, a polynomial of degree up to $n - 1$ will be needed to fit the data exactly. The larger the number of data sets specified, the more accurate the fit will become.

The capability of MATHEMATICA is used to extract the data from the HADRIAN output file and also to put that data into the form to be used to fit functions. These are functions that allow the user to be accommodated in the optimisation problem. Functions have to be written for each user with regard to every object that has to be optimised. Categorisation of these data according to the user and the object is also done in MATHEMATICA.

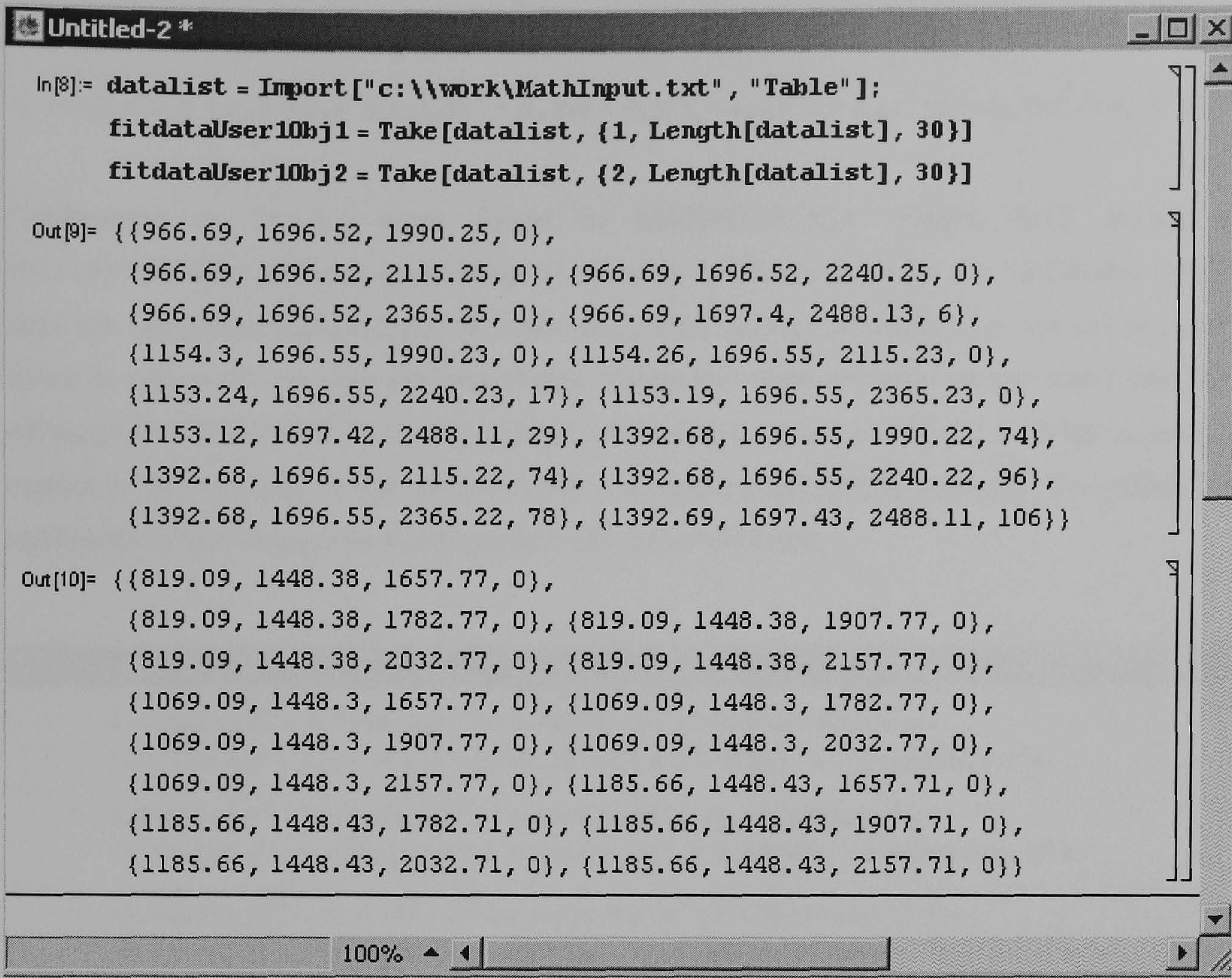
The data file is imported from the file MathInput.txt and read as a table, with the code:

```
Import ("c\\work\MathInput.txt", "Table")
```

MathInput.txt is the edited numbers only, HADRIAN output file.

Then this table is sorted on the basis that the original file contained data regarding n users, p objects and q positions of the object. That is, the data sets were obtained by varying the position of an object q times for each user. This means that there are q data points that can be used to fit functions. For example, the HADRIAN output file shown in Figure 5.7 contained data on 10 users for 3 objects and for each user 15 positions of an object.

Figure 5.12 shows a part of a MATHEMATICA notebook illustrating the code that extracts data from the table obtained from the edited HADRIAN file. It also shows data obtained for two users in the form {x, y, z, out of reach} for 15 positions for each user. The x, y, z co-ordinates in this refer to the new shifted coordinate system. The original coordinate system was shifted by a large positive number using VB code to eliminate the negative coordinate values. This is to enable MATHEMATICA to fit functions without the use of complex numbers which it does if there are any negative values in the data points.



```
Untitled-2 *
In[8]:= datalist = Import["c:\\work\\MathInput.txt", "Table"];
        fitdataUser1Obj1 = Take[datalist, {1, Length[datalist], 30}]
        fitdataUser1Obj2 = Take[datalist, {2, Length[datalist], 30}]

Out[9]= {{966.69, 1696.52, 1990.25, 0},
         {966.69, 1696.52, 2115.25, 0}, {966.69, 1696.52, 2240.25, 0},
         {966.69, 1696.52, 2365.25, 0}, {966.69, 1697.4, 2488.13, 6},
         {1154.3, 1696.55, 1990.23, 0}, {1154.26, 1696.55, 2115.23, 0},
         {1153.24, 1696.55, 2240.23, 17}, {1153.19, 1696.55, 2365.23, 0},
         {1153.12, 1697.42, 2488.11, 29}, {1392.68, 1696.55, 1990.22, 74},
         {1392.68, 1696.55, 2115.22, 74}, {1392.68, 1696.55, 2240.22, 96},
         {1392.68, 1696.55, 2365.22, 78}, {1392.69, 1697.43, 2488.11, 106}}

Out[10]= {{819.09, 1448.38, 1657.77, 0},
          {819.09, 1448.38, 1782.77, 0}, {819.09, 1448.38, 1907.77, 0},
          {819.09, 1448.38, 2032.77, 0}, {819.09, 1448.38, 2157.77, 0},
          {1069.09, 1448.3, 1657.77, 0}, {1069.09, 1448.3, 1782.77, 0},
          {1069.09, 1448.3, 1907.77, 0}, {1069.09, 1448.3, 2032.77, 0},
          {1069.09, 1448.3, 2157.77, 0}, {1185.66, 1448.43, 1657.71, 0},
          {1185.66, 1448.43, 1782.71, 0}, {1185.66, 1448.43, 1907.71, 0},
          {1185.66, 1448.43, 2032.71, 0}, {1185.66, 1448.43, 2157.71, 0}}

100%
```

Figure 5.12 - Sorted data for 2 users in a MATHEMATICA notebook

The first set of data shown is for user 1 and for 15 positions of object 1. Then the problem becomes fitting a function to this data for variables x, y and z.

MATHEMATICA can be used to fit curves that have any number of variables. In SHIELDS, the optimisation will be limited to free design parameters of the product or workplace. Since the total design problem is broken down into individual objects for the optimisation the free design parameters for each of these objects are taken as the variables for the user centred objective functions. Usually the number of dependent free parameters in any one of these objects is limited to 6 or less. They are three degrees of freedom in translation in x, y and z directions and three degrees of freedom in rotation in α, β, and θ directions. Therefore the SHIELDS modelling and optimisation functions are constructed only for 6 variables, but if the need arises it can easily be extended to any other number of variables because of this capability of MATHEMATICA.

The functions thus fitted are then used in the optimisation process as user centred objective functions. These are the functions that incorporate the user in the optimisation. Solution to the whole design synthesis problem that strives to achieve the inclusive design concept lies with these equations.

Functions that fitted the form of data obtained from HADRIAN analysis are of the form:

$$a_1 + a_2 x + a_3 y + a_4 z + a_5 x^2 y + a_6 x y^2 + a_7 xyz + a_8 y^2 z + a_9 x y^2 z + a_{10} x^2 yz + a_{11} xyz^2 + a_{12} x^2 y^2 z^2$$

Coefficients a_1 to a_{12} were found in MATHEMATICA. Figure 5.13 shows a MATHEMATICA notebook containing 10 of these functions fitted for the HADRIAN output data file discussed earlier. Each of these equations defines a function for the out of reach value of that particular user and the object. These functions are then written into a text file. Although MATHEMATICA has the ability to format this output text file to a certain extent, it cannot write it exactly in the form that can be read by SWORDS software. Therefore the MATHEMATICA output file is also edited using the VB code.

Obj-1.nb

$$1.11668 \times 10^{11} - 5.98087 \times 10^{7} x - 6.58199 \times 10^{7} y + 0.000513167 x^2 y + 20.7785 x y^2 - 2.24348 \times 10^{7} z + 28.3299 x y z + 7.7943 y^2 z - 0.0166982 x y^2 z$$

$$2.90198 \times 10^{10} - 1.60964 \times 10^{7} x - 1.71048 \times 10^{7} y + 0.000256811 x^2 y + 5.59199 x y^2 - 5.83028 \times 10^{6} z + 7.62442 x y z + 2.02552 y^2 z - 0.00449393 x y^2 z$$

$$-5.34904 \times 10^{10} + 2.51838 \times 10^{7} x + 3.15299 \times 10^{7} y + 0.000593407 x^2 y - 8.75049 x y^2 + 1.07462 \times 10^{7} z - 11.9291 x y z - 3.73377 y^2 z + 0.00703173 x y^2 z$$

$$3.49477 \times 10^{10} - 1.84886 \times 10^{7} x - 2.05991 \times 10^{7} y + 6.42333 x y^2 - 7.02112 \times 10^{6} z + 8.75755 x y z + 2.43931 y^2 z - 0.00516192 x y^2 z$$

$$-7.81016 \times 10^{10} + 4.0268 \times 10^{7} x + 4.60355 \times 10^{7} y - 13.9903 x y^2 + 1.56909 \times 10^{7} z - 19.074 x y z - 5.45146 y^2 z + 0.0112428 x y^2 z$$

$$-7.53529 \times 10^{10} + 4.09615 \times 10^{7} x + 4.44146 \times 10^{7} y - 0.000509448 x^2 y - 14.2305 x y^2 + 1.51389 \times 10^{7} z - 19.4025 x y z - 5.25952 y^2 z + 0.0114361 x y^2 z$$

$$-3.42087 \times 10^{11} + 1.78567 \times 10^{8} x + 2.01636 \times 10^{8} y - 0.000451282 x^2 y - 62.0386 x y^2 + 6.87269 \times 10^{7} z - 84.5829 x y z - 23.8776 y^2 z + 0.0498555 x y^2 z$$

$$-5.33351 \times 10^{10} + 2.75816 \times 10^{7} x + 3.14374 \times 10^{7} y - 9.58265 x y^2 + 1.07153 \times 10^{7} z - 13.0648 x y z - 3.72279 y^2 z + 0.0077008 x y^2 z$$

$$2.2187 \times 10^{10} - 1.14746 \times 10^{7} x - 1.30777 \times 10^{7} y + 3.98659 x y^2 - 4.45749 \times 10^{6} z + 5.43529 x y z + 1.54866 y^2 z - 0.00320371 x y^2 z$$

$$-5.9229 \times 10^{10} + 3.15822 \times 10^{7} x + 3.4911 \times 10^{7} y - 0.000240837 x^2 y - 10.9722 x y^2 + 1.18994 \times 10^{7} z - 14.9597 x y z - 4.13411 y^2 z + 0.00881755 x y^2 z$$

100%

Figure 5.13 - Functions written for the HADRIAN output data

SWORDS macros are written in text editors using a language that has characteristics similar to BASIC. After going through the editing process, the equations written in MATHEMATICA must be read directly into these macros while they are being processed in SWORDS, for the whole process to be efficient. A problem was encountered here because the SWORDS software was not able to read large equations such as those equations written by MATHEMATICA. This problem was overcome by writing the whole SWORDS macro using VB code.

Then the whole optimisation problem is modelled by using VB and formulated into constraint models in these macros. The added advantage of using VB was that the constraints that the users of SHIELDS have specified could also be read and added to the macro at this stage through user interface. There are a series of SWORDS macros to cater for each scenario depending on the number of objects in the workplace and the number of variables in the model. SHIELDS selects the required macro and invokes SWORDS in the background to optimise the model.

Figure 5.14 shows a sample of a SWORDS macro that is used to optimise just one of the user-centred objective functions which contains three dependent variables. The SWORDS constraint modeller tries to make the UOF equal to zero within the given constraints for these variables.

Out of several optimisation methods in SWORDS, the Hooke and Jeeves method without random start was used in these macros. This was found to be the best method to optimise large equations. It starts the optimisation process with just one random starting point. Although this works well, sometimes it may lead the optimisation process to find a local minimum rather than a true optimum point. These problems can be overcome by specifying an initial value. This initial value, which can be specified through the user interface, can be decided upon by examining the position of the object under evaluation. The first line of the SWORDS macro shown in figure 6.5.1 specifies this optimisation method as *optmethod(4)* which is the Hooke and Jeeves method without random start.

In SWORDS the 'function' statement starts a user-defined function. Inside this, the objective functions and the constraints for the variables are defined. '*funca*' in Figure 5.14 was specified as *'aa'* and inputs were given as *'funca(xx, yy, zz)'*. These *xx, yy, zz* are *x, y, z* variables made global by declaring them at the beginning of the macro. For the processor to change the values of the variables during the optimisation process, the variables have to be made 'free' by specifying them with the command *'var'*. Only the variables thus made 'free' will be varied for the optimisation. Then the 'rule' command is used to specify objective functions or constraints that need to be made true.

Any valid algebraic expression involving the defined variables can be used in rules. The values of each of these expressions, which are treated as real numbers, should be zero when they are true. The falseness of the expression is measured by the absolute value of this expression. The SWORDS constraints solver attempts to make all rules in a user-defined function true, by manipulating the free variables. If some of the rules in the user defined function can't be made true it tries to minimise the sum of the squares of the rule values. The objective function in this example is specified by the line *rule (w2*aa)*. If there is more than one objective function and they all depend on each other they can be given within one function. When there are several individuals in the evaluation of an object, user-centred objective functions that relate to them have to be written within one SWORDS function because they all depend on the same set of variables.

```
optmethod (4);
dec real xx, yy, zz;
dec real aa, bb, cc, dd, ee;
dec real ff, gg, hh, ii, jj;
dec real w1, w2;

w1 = 1.0;
w2 = 1.0;

function funca
{
dec real x, y, z, a;
inp  x, y, z;
out  a;
a = -2.2897*10^6 + 1459.8597*x + 1181.7441*y -
 115*10^-6*x^2*y – 341*10^-6*x*y^2 +
 746.7297*z – 109*10^-4*x*y*z +
 1.1592*10^-7*x^2*y*z – 164*10^-4*y^2*z +
 4.8133*10^-7*x*y^2*z – 419*10^-6*y*z^2 +
 6.9856*10^-8*x*y*z^2;
}
function reach
{
 var  xx, yy, zz;
 aa = funca( xx, yy, zz );
 rule ( w2*aa );
 rule ( w1*(xx .gt. 750) );
 rule ( w1*(xx .lt. 1250) );
 rule ( w1*(yy .gt. 1400) );
 rule ( w1*(yy .lt. 2000) );
 rule ( w1*(zz .gt. 1600) );
 rule ( w1*(zz .lt. 2100) );
}
```

Figure 5.14 - An example of a SWORDS macro

w1 and w2 in this example are weighting factors. In situations where all the rules cannot be made true at once, the system tries to satisfy the rules that have the largest effect on sum of the squares of the rule values. This can be used to manipulate rules macros by multiplying rules that have to be satisfied, by large weighting factors. In SHIELDS programming, these weighting factors were used to give the emphasis to the users or to the constraints of the parameters of the product or workplace.

5.5.1 Formulation and Satisfaction of Constraints

Constraints form a very important part of the design problem. They determine the feasibility of a design by limiting the values of the free variables. These constraints can be referred to the size of the design or its functionality. The designer identifies most of these constraints at the problem formulation stage. Often they are easier to identify after the total design problem has been decomposed into individual objects. Then the constraints relating to each of these objects are formulated and by examining the total problem, any relationships between these constraints that relate each of these objects to others in the design, are identified. These relationships between the constraints bind the whole design problem back together.

After all these constraints have been identified, they need to be written in terms of free design parameters. Then they are included in the SWORDS macro inside one of its function statements together with objective functions. Constraints are also specified as 'rules' in the macro. All the objective functions and constraints that affect each other are put together inside a single SWORDS function. If there are any objective functions or constraints that are independent they are put in separate functions.

The function 'reach' in the example illustrated in Figure 5.14 contains several constraints. Following sample of code shows these constraints.

```
function reach
{
var  xx, yy, zz;
aa = funca( xx, yy, zz );
rule ( w2*aa );
rule ( w1*(xx .gt. 750) );
rule ( w1*(xx .lt. 1250) );
rule ( w1*(yy .gt. 1400) );
rule ( w1*(yy .lt. 2000) );
rule ( w1*(zz .gt. 1600) );
rule ( w1*(zz .lt. 2100) );
}
```

They have been written for the constraints for free variables x, y and z. Those constraints written in mathematical form are:

$$750 < x < 1250$$

$$1400 < y < 2000$$

$$1600 < z < 2100$$

Equality constraints such as $200\,x_1 + 460\,x_2 = 4000$, are written as;

$$rule\ (200\,x_1 + 460\,x_2 - 4000)$$

in the SWORDS macro.

w1 in the above example is the weighting factor specified for the constraints. Although different weighting factors can be specified for each constraint, in this example all constraints were treated with equal priority. Values for these weighting factors can be assigned according to the specific requirements. For example, in this case where w2 was assigned to the user-centred objective function and w1 was assigned to the constraints, specifying a larger w2 would ensure priority being given to the objective function. That is, if some of the rules cannot be satisfied, then the constraint modeller will try to satisfy the rule that contains the objective function because it has been multiplied by the larger weighting factor.

Usually however, it is the constraints of the design that need to be satisfied first to obtain a feasible design. If there are some constraints that must be satisfied and some that can be relaxed this is also done through the weighting factor by specifying different values depending on importance. The SHIELDS user interface allows the designer the functionality to specify these weighting factors.

When trying to achieve Inclusive Design objectives, a large number of UOFs have to be considered in the optimisation together with the constraints for a single object in the design. All these expressions for an object were put inside a single 'function' in the SWORDS macro. Therefore, if there is more than one dependent object then formulae regarding them are also written in the same SWORDS function in the macro. These different kinds of conditions were accommodated in the SHIELDS software by including several macros as Visual Basic modules and allowing the software to select the appropriate module by identifying the number of objects.

The SWORDS constraint modeller, which can accommodate a large number of free variables, runs through a large number of iterations to find the optimum solution. The maximum number of iterations that are to be used by the SWORDS modeller before conceding failure can be specified in the macro. The value of a rule below which a truth-value is considered to be 'true' can also be specified. The value of an expression given as a rule is considered to be 'true' when it is zero. The default value that is considered to be 'true' is 1×10^{-5}.

After the constraint modeller has found suitable values for the variables, these values and the resulting values of the UOFs are written to a text file. These results are then used to get the SHIELDS output of the new design parameters and also which of the users have been successful in achieving the specified tasks. SHIELDS provides this data as new parameters of the design and the users who can and cannot use the design.

These parameters can then be used to modify the HADRIAN model and perform the evaluations again and find out if they affect anything else in the product or the workplace.

The software was tested at each stage, by evaluating the code, the components and then all of it together.

5.6 The User Interface Design

The SHIELDS user interface was designed primarily to provide a fully functional software tool to aid designers in their quest to achieve the Inclusive Design concept by enabling them to predict the design parameters. The fact that SHIELDS uses three different pieces of software makes it harder to establish a smoothly functioning interface. Visual Basic was used to build SHIELDS, to edit various output files and also to design the user interface. In VB environment 'forms' are used to create screens and windows that embody the user interface of the newly created programme. On these forms a user can draw buttons, input boxes, graphics etc. that make up the user interface.

The SHIELDS user interface allows the user firstly to build a new model or open an existing model by opening HADRIAN. Rather than just accessing HADRIAN capability through a link, the whole HADRIAN package is opened to be used by the designer. This was done because to build a model and to evaluate it, SHIELDS uses all of HADRIAN's capabilities and its database. Therefore, building another user interface to do it all would have been a duplication of work and an unnecessary waste of time. The designer thus builds the model and evaluates it by accessing HADRIAN via SHIELDS interface. After this, if there is a necessity to optimise, that is, if there are any objects that failed the user accommodation criteria, the designer runs a programme to get the 'failure values' and these values are automatically saved into a text file.

The next step in the optimisation process is the specification if the objects that are to be optimised, to the system. This is done through the input controls shown in the screen illustrated in the Figure 5.15

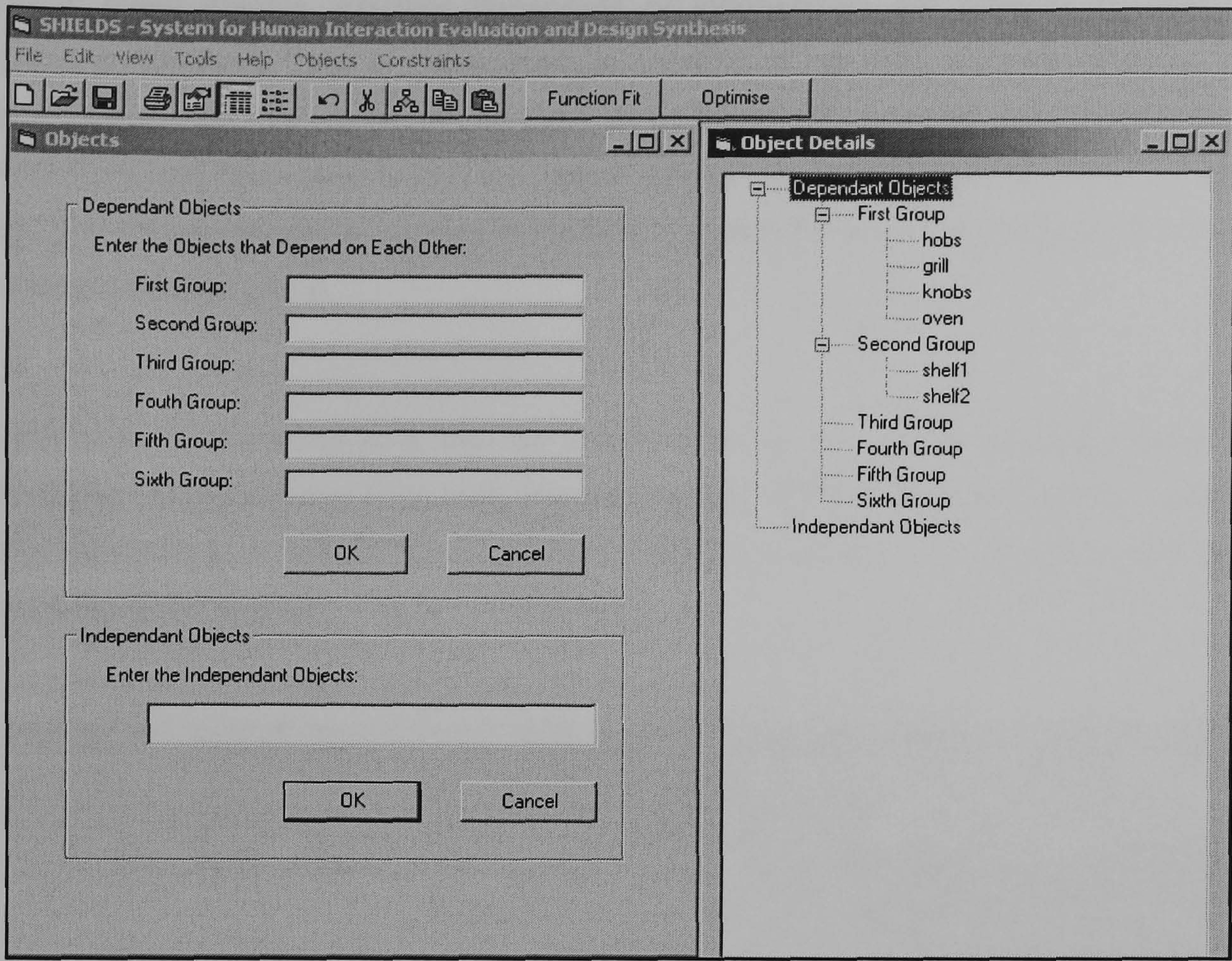


Figure 5.15 - A screen shot from SHIELDS

In it, provisions are made for two types of objects to be specified. The first type is for the dependent objects in the design. The total design is decomposed into manageable smaller objects for the optimisation. These objects, repositioning or resizing of which affect others are taken as dependent objects. There can be several groups of these dependent objects in a complicated design. For example, in a kitchen design, if the redesign of a cooker is allowed, the objects in the cooker can be taken as one group while the shelves can be taken as another. They are taken as two groups because while the objects on the cooker do depend on each other they do not affect the shelves but the position of one shelf affects the rest of the shelves. The independent objects are objects repositioning or resizing of which do not affect any other object. There is a provision to specify these as well.

Categorisation of these dependent objects into groups is extremely important to the proper functioning of SHIELDS because the number of objects in a particular group determines the selection of MATHEMATICA programme and the SWORDS macro that the system uses to optimise these objects. Although the system chooses these programmes and macros automatically, the designer has to decide what the dependent objects are and how to form the groups. The designer can view all the specified objects in the tree view shown in the above figure.

Each of these objects, whether dependent or independent are allowed to have six degrees of freedom. That is, the system is capable of handling six free variables per object. User-centred functions can be fitted for all these objects using all of the variables, if HADRIAN had been used to find the 'failure values' by varying these variables for each user. This is done simply by clicking the button 'Function Fit' shown in the figure 5.6.1 and choosing an object group.

Specification of the constraints can be done before or after fitting these functions but optimisation must be done after both the specification of the constraints and the function fitting have been completed. Figure 5.16 illustrates the input controls that are used to input constraints to the system.

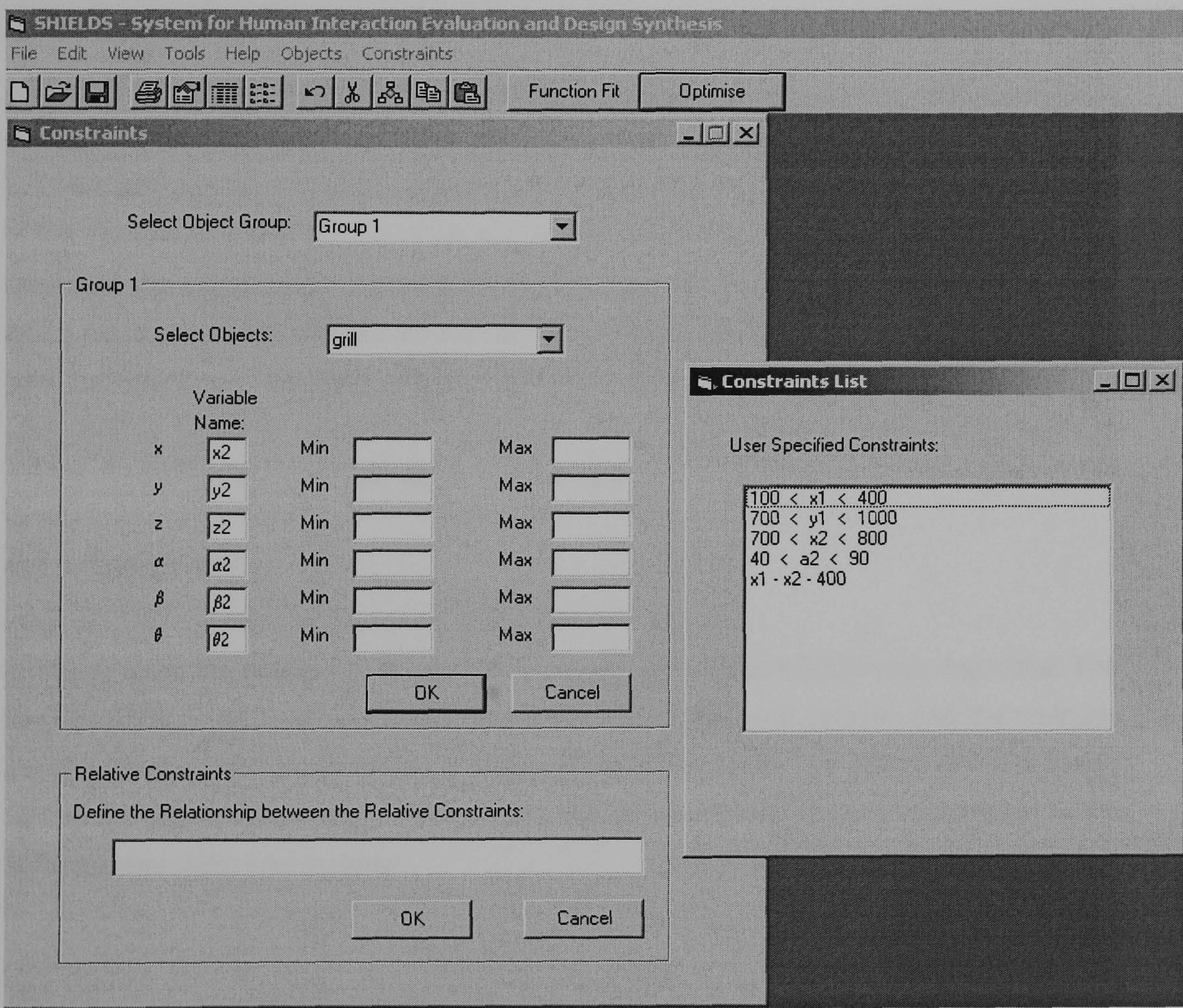


Figure 5.16 - A screen shot of SHIELDS showing the constraints

To define constraints, first of all the designer must identify them from the design considering all the aspects of the design. These constraints are usually applied to the objects and not the users because all the constraints of the users have been taken into account when formulating the user-centred objective functions. Then the designer has to select the group the specific object belongs to from the previously defined list, which is shown on the top of the screen. Then the list of objects belonging to that group will appear below and the designer then selects the object to add the constraints. Constraints can be added to all three translations of the object in x, y and z directions and the three rotations in α, β and θ. The designer can add minimum and maximum values for these variables.

Then for the dependent objects, relative constraints can be added in the input control at the bottom of the screen. These must be added as an expression and not as an equation. For example, if the constraint is $x_1 - x_2 = 400$ for the objects one and two, it should be defined to the system as $x_1 - x_2 - 400$. This is to simplify the coding since these constraints will be added to the SWORDS macros through VB code. All these constraints can be viewed in a list as shown in Figure 5.16.

After fitting functions and defining constraints, objects can be optimised very simply by clicking the button 'Optimise' and choosing an object group. This will access SWORDS software and will run the appropriate macro for the selected group. This will be performed in the background and the designer will be presented with the screen showing only the results of the optimisation. These results will consist of the new values for the variables and a list of users who can and cannot use the object in the new position or the object that with the new size. The users are defined to the system automatically by the use of the user-centred objective functions. These new values can be used again in HADRIAN to modify the design and evaluate again if necessary.

5.7 Summary

In this chapter the method of developing the new software SHIELDS was described. The functionalities of each of the components within SHIELDS were detailed and the methods used to utilise these functionalities in SHIELDS was described. The design of the software was discussed in the view of accomplishing the requirements. The implementation of the software was described in detail.

The next chapter presents a case study that further tests the capabilities of SHIELDS. It also tests the links between the software used and the methodology behind it.

Chapter 6

The ATM Case Study

6.1 Chapter Overview

A case study involving an Automated Teller Machine (ATM) is described in this chapter. The case study method and how the specified objectives were achieved are demonstrated. This case study was used to test SHIELDS capacities in incorporating the consumer of a product in the design process. Also how to optimise the layouts of two objects, positions of which are dependent on each other is analysed.

6.2 Description of the Case Study

Automated teller machines (ATM) are used to obtain cash by inserting a plastic card and a pin number. Since its introduction to the people its popularity has grown a thousand fold because it provides a convenient method of obtaining cash. People with all abilities use ATMs or wish to use them. Hence it is important to include all the user population in the design of ATMs.

6.2.1 Importance of the ATM case study with regard to the project presented in this thesis

The research presented involves the maximisation of user accommodation in a product including disabled and elderly people. The method developed by this research will incorporate all the users of a product and the factors concerning the layout of the product or workplace. To test this method and to make the effort worthwhile it is important to perform a case study that involves people with all abilities and a product that has importance to the general public. To test the functionality of the software developed it is important to test it against a product that has a wide range of issues.

The ATM satisfies these in the following ways.

- As described in the previous sections, the ATM is becoming a part of the everyday life in the modern society, making it a very useful product
- People of all ages and abilities want to and need to use it, which gives a very good incentive to make the ATM inclusive with respect to users

- Physical features of the ATM consist of several objects such as the screen, keypad, card slot and the cash dispenser and they are constrained into a small space providing an ideal setting to test the proposed methods of user incorporation, decomposition, constraint selection and optimisation.
- ATMs provide sufficient complexity of design with regard to the above mentioned objects in the sense that each object has several degrees of freedom and some of their positions depend on the positions of the others around it.

6.2.2 Tasks performed by users for the interaction with an ATM

There are two main sections of user interaction in the ATMs. One is the physical user interface that comprises the screen, keypad, card slot and the cash dispenser. The other is the information the user reads on the screen and its layout, colours, font size, etc. Both of these must be user friendly for the maximum user accommodation. For the purposes of this case study, only the physical aspects of the ATM are considered.

With regard to these physical factors, the main tasks that a user will need to carry out are

- See the screen
- See and reach the keypad
- See and reach the card slot
- See and reach the cash dispenser

All these depend on the anthropometry of the person and whether that person is standing or sitting and that person's joint constraints such as the ability to bend or lift the hand etc. Ability to perform these tasks also depends on these objects' positions with respect to the ground and the front wall. With regard to the screen, user ability to see the screen and ability to read what is on it depends on its height as well as its angle and also whether the sun is reflecting from it, which can be a huge hindrance. This problem however is being eliminated by the invention of the new sunlight immune liquid crystal display, which utilises a combination of several methods to solve this problem (Ajluni, 1998).

In addition to these considerations, all the features of the ATM must be constrained in to a small area in view of the need for security and privacy.

6.3 Objectives of the Case Study

6.3.1 To test the following hypothesis made in Chapter 1

- The first hypothesis states that the when users failed to complete a task, by obtaining the 'failure values' it is possible to generate a path for this inability and that path can be mapped into a mathematical expression.
- The second hypothesis states that the physical aspects concerning the users and the design as well as the constraints can be expressed in mathematical terms in order to use them in an optimisation process.
- The third hypothesis states that the Inclusive Design problem can be formulated in such a way as to be able to implement it in a software system to be solved by an optimisation process.

6.3.2 To test links between the software

6.3.3 To find out SHIELDS capability to optimise at least two interdependent objects

6.3.4 To find out SHIELDS capability to incorporate characteristics of the users of products or workplaces in the design process

6.4 Methodology

The new software SHIELDS optimisation process follows the steps below.

- Model building – generally this is done in SAMMIE. But a CAD model built in another software also can be read into SAMMIE/HADRIAN
- HADRIAN evaluation – the model built is evaluated in HADRIAN using its database of users
- Components/objects selection for optimisation (decomposition) – the designer who uses SHIELDS does this by analysing the HADRIAN output and then these are input into the system in groups
- Object grouping – Objects separated above are grouped together according to how their positions affect each other.
- Constraint selection for each of the degrees of freedom for every object as well as the selection of relative constraints – again this has to be done by the SHIELDS user
- HADRIAN analysis to obtain 'out of reach' or failure values for the objects used for optimisation
- Function fitting – this is done using MATHEMATICA

- Optimisation using SWORDS software

6.4.1 The Physical ATM User Interface and Model Building

To test the functionality of SHIELDS, the ATM used is a general machine with typical layout. A line diagram of the ATM used in the case study is shown in Figure 6.1 with many of the dimensions used to build the model in HADRIAN and to perform the initial HADRIAN evaluation.

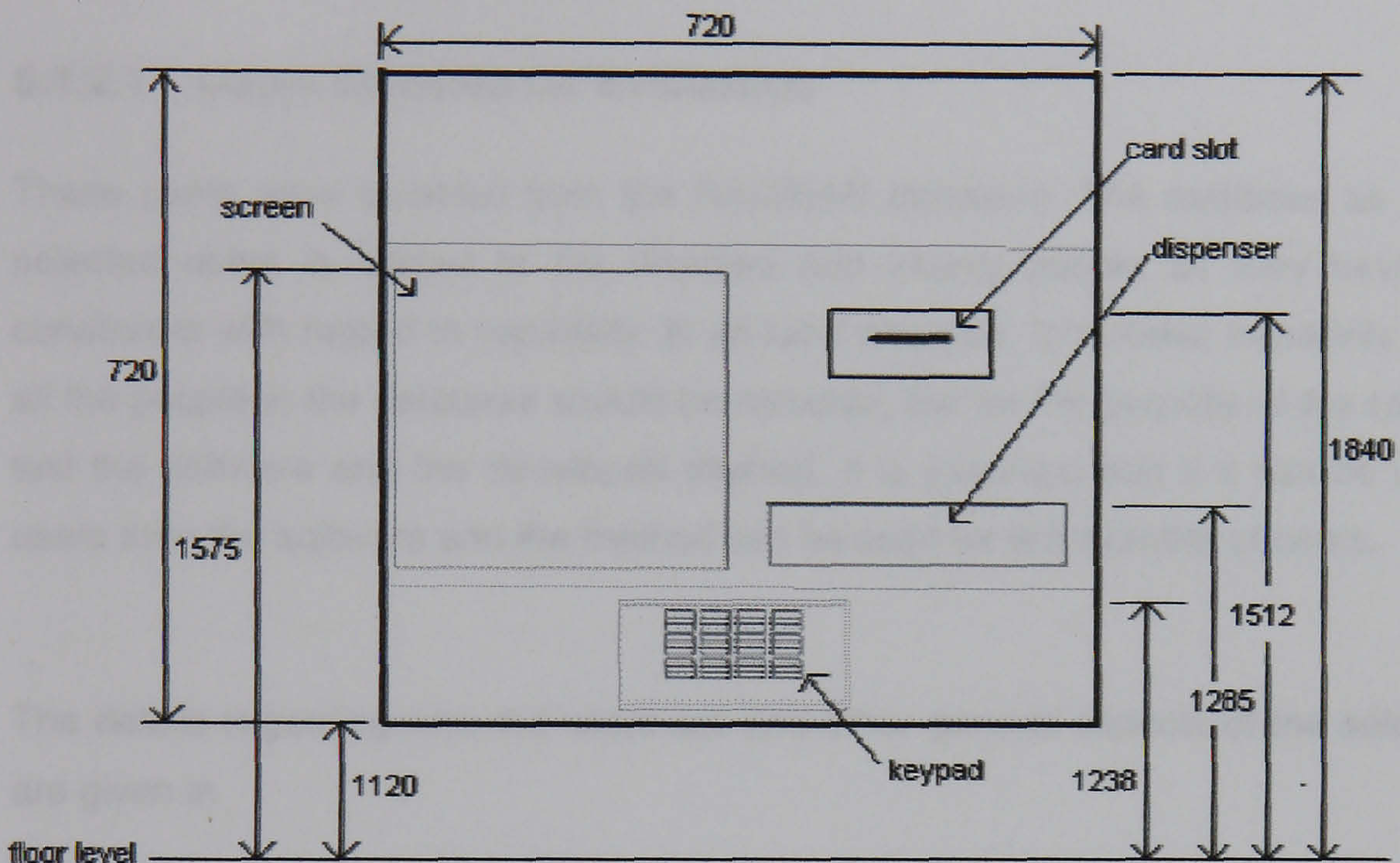


Figure 6.1 – ATM User Interface

The figure shown above consists mainly of the 'z' dimensions used to build the model. The whole model was built using SAMMIE. For this case study, an ATM model built on SAMMIE as illustrated in Figure 6.2, by the 'design for all' project group was used with the kind permission of the HADRIAN developers.

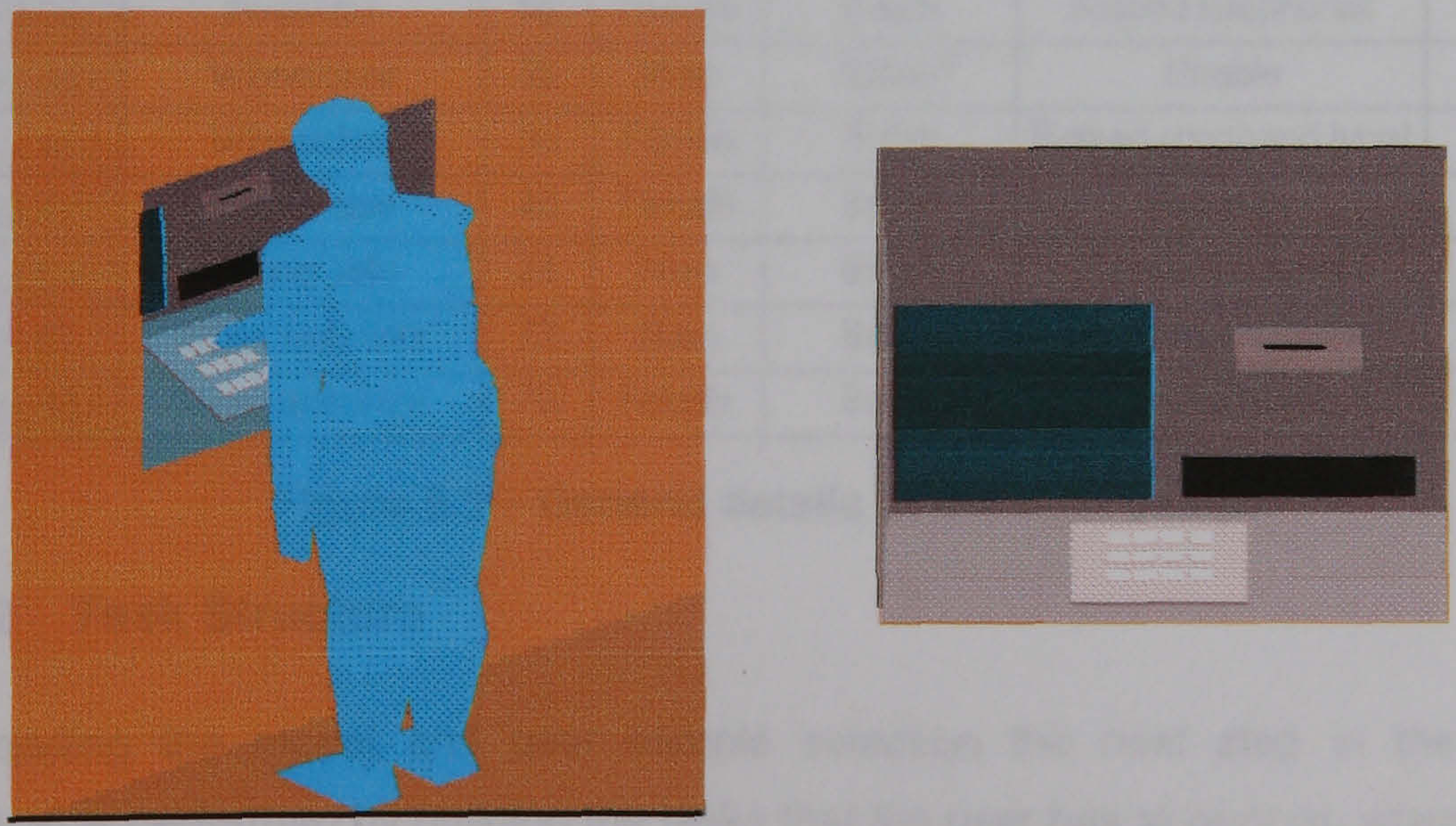


Figure 6.2 – ATM Model Built on SAMMIE

6.4.2 HADRIAN Evaluation

This is done firstly by loading the model into HADRIAN and choosing a 'target population' from the in-built database. This 'target population' is assumed to be the set of users who will ultimately use the product. HADRIAN contains a rich database of 100 users and any number from that can be selected for the evaluation. For the purpose of this case study a sample of 10 users was selected.

6.4.2.1 Users Selected for Evaluation

These users were selected from the HADRIAN database. The database as well as the selected users is biased to the disabled and elderly people as they have the most constraints with regard to capability. In an ideal situation, to achieve inclusivity in a design all the people in the database should be selected. But for the purpose of the case study to test the software and the developed method, it is assumed that if it can be used for 10 users then the software and the method can be used for any number of users.

The details regarding who the users are and other general aspects of the selected users are given in

Figure 6.3. Other details of the users such as their disability, vision, somatotype, weight, anthropometric details, capability and constraints etc. are also given in the database.

Full Data: Data Sets 1 - 98

	Category	Age	Gender	Nationality	Occupation	Handed
Subject 11	Older able	72	Female	British	Retired office worker	Right
Subject 12	Older able	73	Male	British	Retired electrical	Right
Subject 27	Ambulant	61	Male	British	Retired plumber &	Right ambi
Subject 28	Ambulant	56	Female	British	Retired telephonist	Very right
Subject 40	Wheelchair	36	Male	British	Unable	Very left
Subject 41	Wheelchair	56	Female	British	Retired shorthand typist	Right
Subject 47	Young able	40	Female	British	Secretary	Right ambi
Subject 54	Young able	24	Male	British	Research student	Right
Subject 97	Older ambulant	73	Male	British	Retired engineer	Very right
Subject 98	Older ambulant	79	Female	British	Retired nurse	Very right

Figure 6.3 – General details of the user sample

6.4.2.2 Task Structure

After loading the model and user sample selection the next step in the HADRIAN evaluation is performed by building the tasks that the user has to perform when interacting with the product. With an ATM people have to perform the tasks described in section 6.2.4.

For example, the users have to see and reach the keypad. In the HADRIAN task builder these tasks are assigned with the commands 'LOOK' and 'REACH' and a specification of which objects to look at and reach to. In the case of reach other aspects such as whether to reach by hand and then whether left or right hand and the type of grip such as fingertip or thumb etc is specified.

The main task the users perform when using the ATM is obtaining cash by inserting a plastic card and punching out the necessary details on the keypad. To perform this they have to be able to see the screen, the keypad, card slot and the cash dispenser and be able to reach these objects except the screen. The detailed structure of these tasks and their associated task elements are described below. This task structure was then specified into HADRIAN using the task builder provided in the HADRIAN user interface.

Overall Task: Obtain cash from the ATM

To perform this task successfully the users have to be able to perform the tasks and the task elements described below.

Task 1: Move in front of the ATM

Task 2: Face the ATM

Task 3: View the screen

Task 4: Insert/ get card

 Task Element 1: View card slot

 Task Element 2: Reach card slot (with left/right hand – thumb tip)

Task 5: Punch required details on the keypad

 Task Element 1: View keypad

 Task Element 2: Reach keypad (with left/right hand – finger tip)

Task6: Get cash/receipt

 Task Element 1: View cash dispenser

 Task Element 2: Reach cash dispenser (with left/right hand – thumb tip)

All the tasks the users of the ATM perform are specified in this way. A screen shot of the HADRIAN task builder is shown in Figure 6.4 that shows how the task structure was constructed.

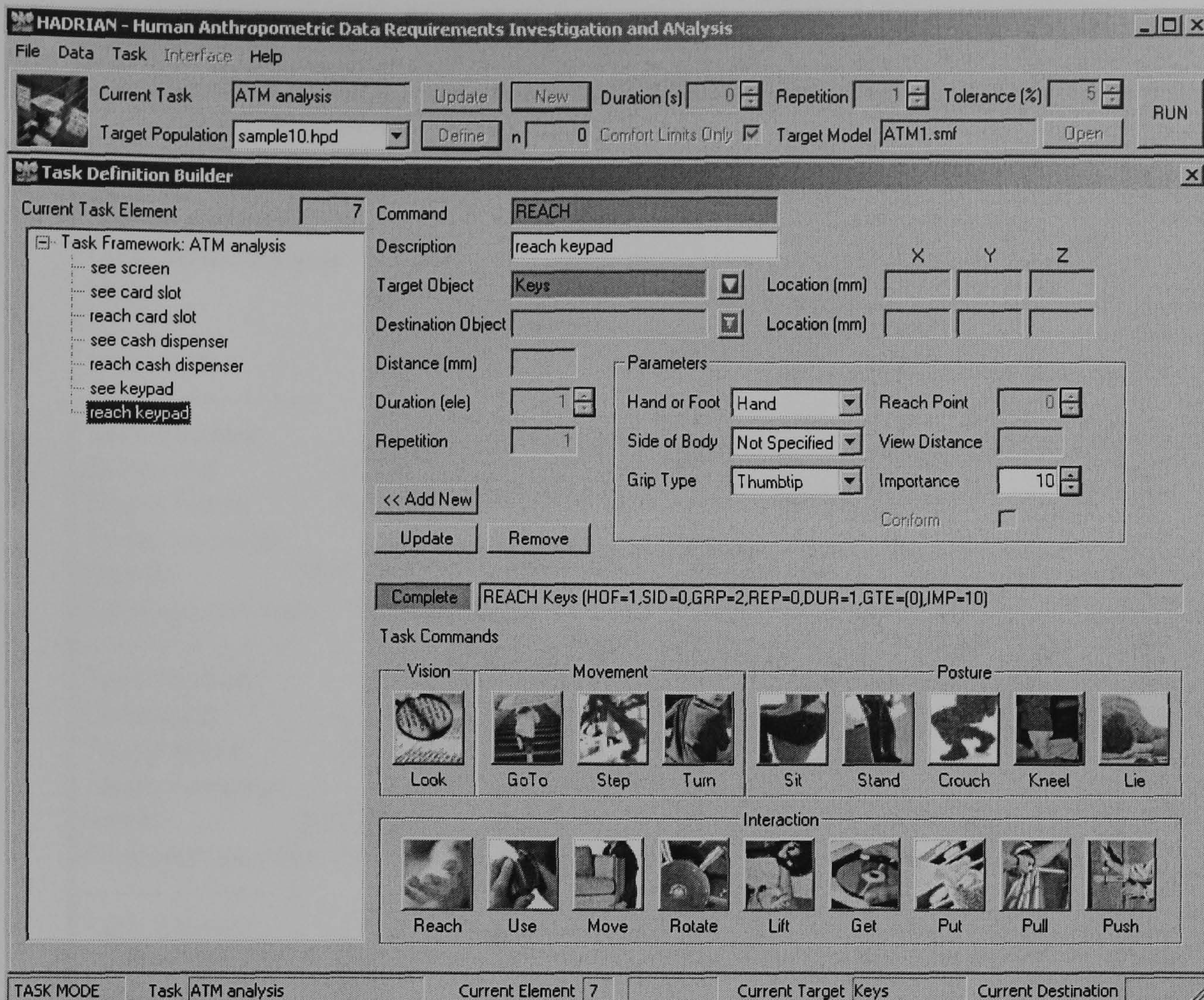
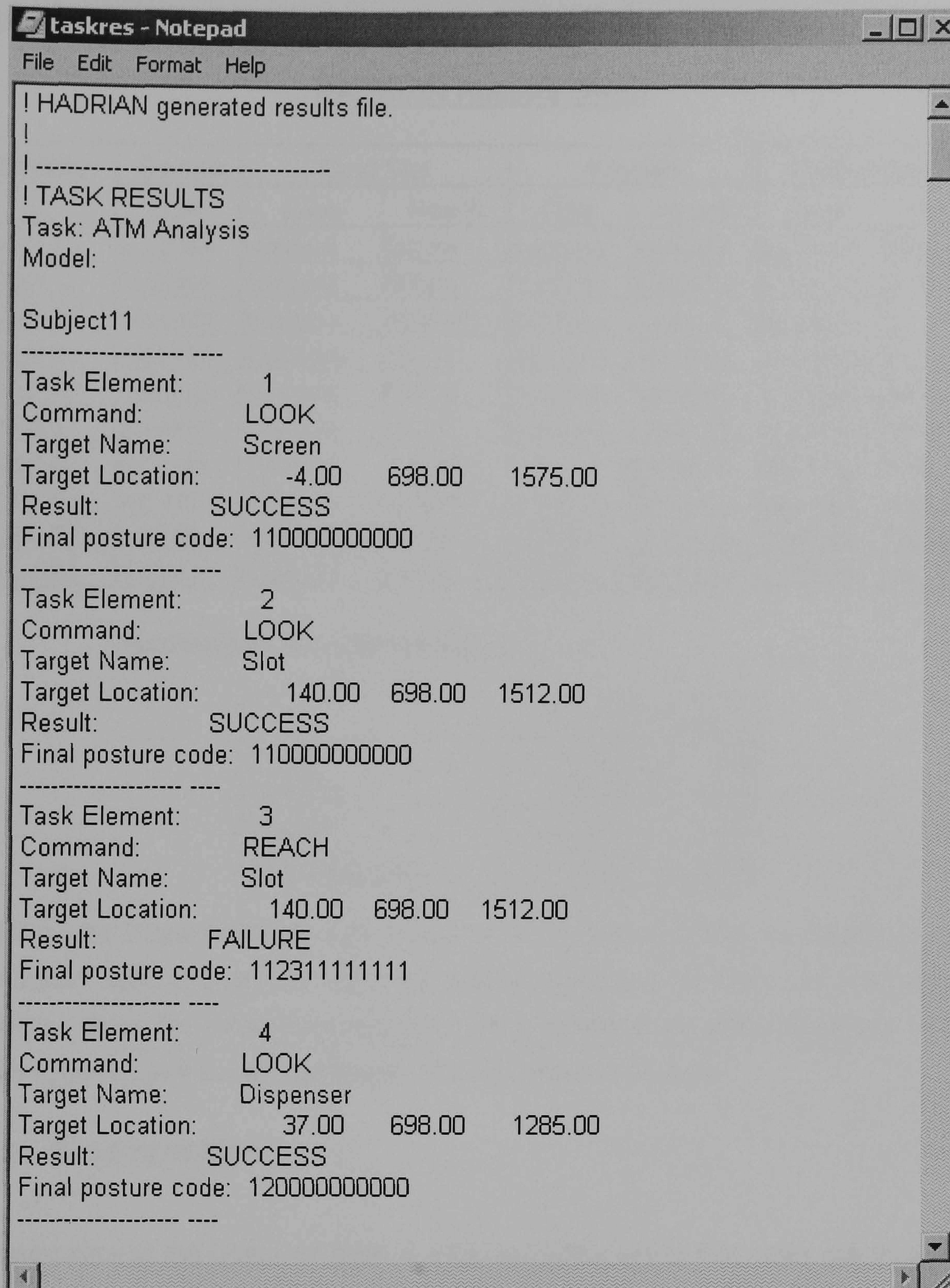


Figure 6.4 – A screen shot of the HADRIAN task builder

After HADRIAN has analysed these tasks it writes the results in to a text file. This file contains all the data regarding the analysis including the object, the tasks performed with respect to the object and who was successful and who failed the tasks. A small portion of this file is shown in Figure 6.5. The whole file is given in appendix 1.

That is, this file provides details on what the command used for that particular analysis is (e.g. REACH) and what the target object is (e.g. Screen) and the target location as well as the results of the analysis. This result can be a success or a failure depending on whether the users were able to perform the required task.



```
! HADRIAN generated results file.
!
! -----------------------------------
! TASK RESULTS
Task: ATM Analysis
Model:

Subject11
-------------------- ----
Task Element:        1
Command:             LOOK
Target Name:         Screen
Target Location:        -4.00     698.00     1575.00
Result:              SUCCESS
Final posture code:  110000000000
-------------------- ----
Task Element:        2
Command:             LOOK
Target Name:         Slot
Target Location:        140.00    698.00    1512.00
Result:              SUCCESS
Final posture code:  110000000000
-------------------- ----
Task Element:        3
Command:             REACH
Target Name:         Slot
Target Location:      140.00    698.00    1512.00
Result:              FAILURE
Final posture code:  112311111111
-------------------- ----
Task Element:        4
Command:             LOOK
Target Name:         Dispenser
Target Location:        37.00     698.00     1285.00
Result:              SUCCESS
Final posture code:  120000000000
-------------------- ----
```

Figure 6.5 – A portion of the HADRIAN out put file

A summary of HADRIAN analysis results for the ATM tasks specified is given in the table below. The detailed results file is given in appendix 1. These results were obtained by analysing the original ATM model before optimisation was performed. This analysis was performed to test the user accommodation of the original ATM model.

Table 6.1 – Results Obtained from HADRIAN Evaluation

HADRIAN Results Sheet

Subjects	Screen	Card Slot		Keypad		Cash dispenser	
	Look	Look	Reach	Look	Reach	Look	Reach
Subject 11	success	success	failure	success	success	success	success
Subject 12	success	success	failure	success	success	success	success
Subject 27	success	success	success	success	success	success	success
Subject 28	success	success	failure	success	success	success	success
Subject 40	success	success	failure	success	success	success	failure
Subject 41	success	success	failure	success	success	success	success
Subject 47	success	success	success	success	success	success	success
Subject 54	success	success	success	success	success	success	success
Subject 97	success	success	success	success	success	success	success
Subject 98	success	success	failure	success	success	success	failure

Percentage Accommodation

	Look	Reach
Screen	100%	n/a
Card Slot	100%	40%
Keypad	100%	100%
Cash dispenser	100%	80%

These results indicate that although all the users are able to see all the objects and reach the keypad, 40% of them can reach the card slot and 80% of them can reach the cash dispenser. Since the target user accommodation for this is the whole sample of 10 users, the analysis is taken to the next stage of the optimisation process.

6.4.3 Decomposition

Decomposition of the design problem is important in the sense that many design problems are complex when they are regarded as a whole but when each of the objects within the design is considered separately, the whole thing becomes simpler. Each of these objects is then optimised separately but within groups of related objects.

The problem is subdivided simply by analysing it and deciding on which objects can be taken separately for the optimisation. The physical user interface of the ATM consists of the objects such as the screen, keypad, card slot and the cash dispenser. However, from the HADRIAN analysis results, it was decided to take only the cash dispenser and the card slot for the optimisation.

The reason for this is that they were the objects that had less than 100% user accommodation. Although all the users were able to view it, the screen and the outer casing of the ATM are also taken into consideration to constrain the other objects.

These objects are then grouped by placing the objects, positions of which affect each other or constrain each other into one group. In the case of the ATM the positions of all the selected objects depend on each other and are constrained by the outer casing. The screen and the outer box of the ATM are considered for the purpose of the application of constraints.

6.4.4 Grouping

This is important for the optimisation process as each group of objects are optimised separately. The designer has to identify which objects have an effect of others when their positions or sizes are changed. Then those objects that affect each other are taken as a group. Constraints that specify these effects are noted and input to the system as relative constraints.

For example in the ATM the screen, the card slot and the cash dispenser which are contained in a single panel must be separated from each other – i.e. there must be a minimum distance between them. Therefore the position of the card slot affects the position of the cash dispenser and the position of the screen. Hence the card slot and the cash dispenser are taken as dependent objects in one group. They must also be within the outer casing and in the panel and must have a minimum distance from the screen. Therefore these constraints are included as relative constraints although the screen and the outer casing are not subject to optimisation. These constraints are described in the following section.

Since the position of the keypad does not affect any other object because it was constrained in a different panel within the outer casing it can be taken as an independent object but still constrained by the outer casing and the panel. However since all the people were being able to reach and see it, it was not taken for the optimisation. After finding better positions for the card slot and the cash dispenser, if the whole ATM has to be moved, a HADRIAN analysis can be carried out to check the new positions for the screen and the keypad.

This grouping is shown in Table 6.1. Although these objects are grouped in this way the configuration of the ATM as a whole is maintained by specifying constraints to all the objects with respect to the outer casing and the panels.

Table 6.2 - Groups of objects in the ATM

Group 1	Independent Objects
Card slot	Keypad
Cash dispenser	
Screen	

SHIELDS provide facilities to include 6 different dependent object groups and any number of independent objects in the menu 'Add Objects'.

6.4.5 Variables and Constraint Selection

Constraints are taken with respect to the product only. All the constraints of the users of the product are taken into account in the HADRIAN analysis. These constraints are selected and decided on by the designer on the basis of the physical aspects such as size and shape of the product and its functionality.

Each of the objects selected have three degrees of freedom of movement in the x, y and z directions. Therefore their x, y and z co-ordinates are taken as the variables for the optimisation. The variables selected are the co-ordinates that can be modified in the search for better positions for the objects selected for the optimisation. In this case for the objects selected, the variables are taken as shown in the Figure 6.6. It is assumed that the size of the ATM and the sizes of its components are fixed and only the positions can be varied. I.e. in the Figure 6.6, *h, e, g, f,* α and θ are constants.

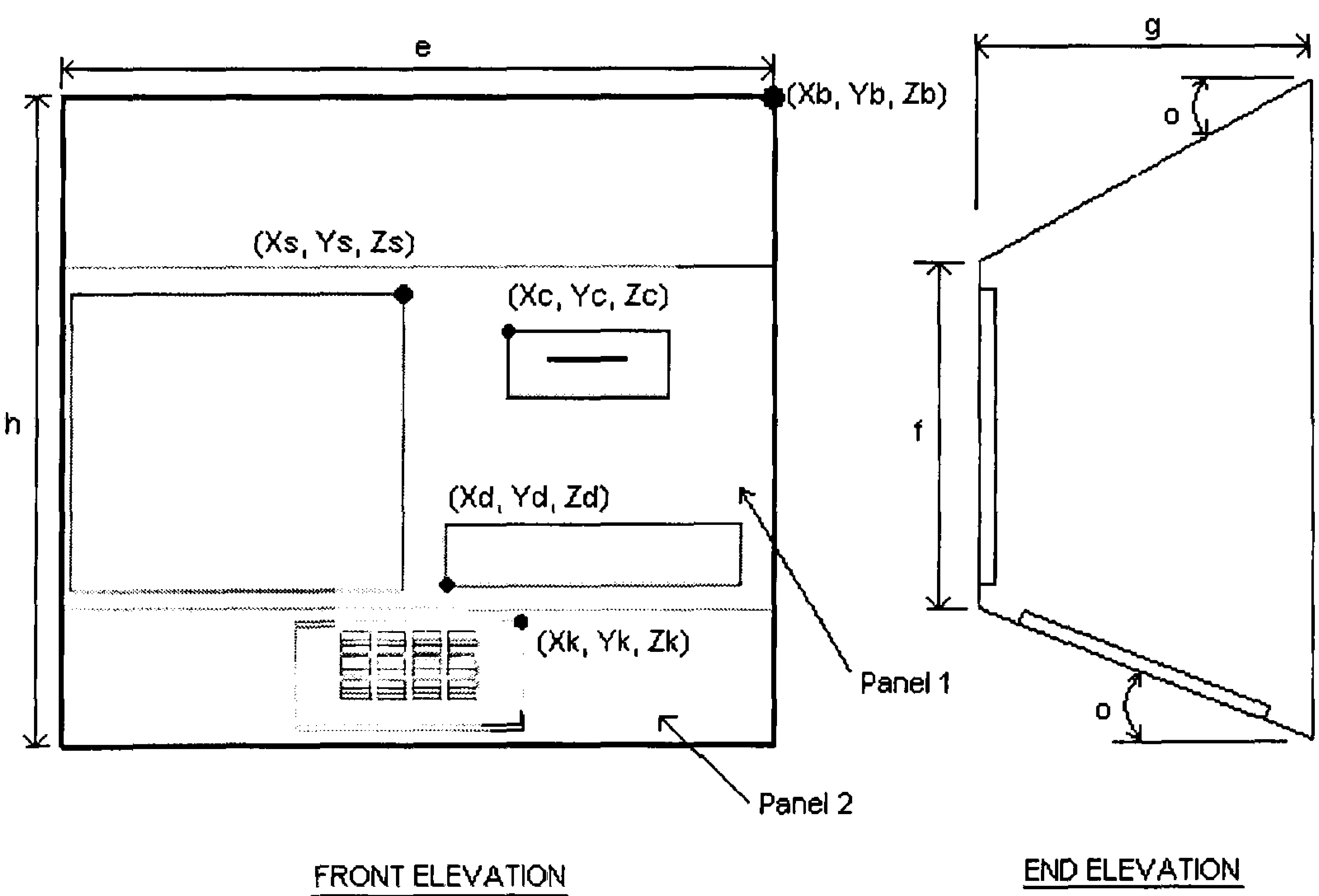


Figure 6.6 – Co-ordinates used in the ATM objects for constraint selection

The constraints are:

- To have a sufficient distance between the card slot and the cash dispenser

$$a < z_c - z_d < b \quad \text{where } a \text{ and } b \text{ are constants} \tag{a}$$

- To have a sufficient distance between the screen and the card slot and cash dispenser

$$c < x_c - x_s < d \tag{b}$$

$$u < x_d - x_s < v \quad \text{where } c, d, u \text{ and } v \text{ are constants} \tag{c}$$

- To contain the screen, the card slot and the cash dispenser on panel 1

$$y_d = y_c = y_s = g \tag{d}$$

$$(x_b - e) < x_c < (x_b - l_c) \tag{e}$$

$$(x_b - e) < x_d < (x_b - l_d) \tag{f}$$

$$\{(x_b - e) + l_s\} < x_s < x_b \tag{g}$$

$$[\{z_b - (g \tan\theta + f)\} + h_c] < z_c < (z_b - g \tan\theta) \tag{h}$$

$$z_b - (g \tan\theta + f) < z_d < \{(z_b - g \tan\theta) - h_d\} \tag{i}$$

$$[\{z_b - (g \tan\theta + f)\} + h_s] < z_s < (z_b - g \tan\theta) \tag{j}$$

where l_c, l_d and l_s are x dimensions and h_c, h_d and h_s are z dimensions of the card slot, cash dispenser and the screen respectively.

- For the keypad to be on the inclined panel 2

$$\{(x_b - e) + l_k\} < x_k < x_b \tag{k}$$

$$w_k < y_k < g \tag{l}$$

$$(z_b - h) < z_k < z_b - (f + g \tan\theta) \tag{m}$$

where l_k and w_k are the x and y dimensions of the keypad respectively.

- To have all the objects within the outer casing

$$z_b > z_c > z_d > z_k > (z_b - h) \tag{n}$$

$$z_b > z_s \tag{o}$$

$$z_b - z_c > p \tag{p}$$

$$z_d - (z_b - h) > q \quad \text{where } p \text{ and } q \text{ are constants} \tag{q}$$

- Minimum and maximum values for all the variables

Of these constraint equations, equations (k), (l), (m) and (o) were not considered in the optimisation process because they relate to the screen and the keypad positions of which were not optimised.

6.4.6 HADRIAN Analysis for the Objects for Optimisation

The next step is quantification of the failures. In other words, to find how much was 'out of reach' or 'out of sight' for each of the users per object. This value is measured in millimetres. A set of values is obtained by varying the positions of each object and testing it with each user. In the case of the ATM, since all the users are able to see all the objects, only the reach values are taken for optimisation. This may prove to be the case for many objects as vision envelopes are much larger than reach envelopes.

Again, this analysis is performed using HADRIAN capability. 'out of reach' distance in millimetres was measured by varying the position of the card slot and the cash dispenser for each user and these results are written to a text file as shown in chapter 5, figure 5.7.

6.4.7 Function fitting

The method presented for incorporation of the users of a product and their capabilities in that product's design optimisation process is based on fitting functions to the data obtained for 'out of reach' or 'out of sight' distances obtained by the above-mentioned process. Since all the users capabilities and constraints are taken into account by the HADRIAN evaluation, it is safe to assume that these capabilities and constraints are represented by these functions fitted for 'out of reach' and 'out of sight' values. The functions are fitted to the data by using SHIELDS 'Function Fit' command and then choosing the object group from the options list.

Then SHIELDS automatically selects the necessary macro and runs MATHEMATICA to fit functions and to write them into a text file. These functions are called the user centred objective functions because they are used in the optimisation process to represent user characteristics. The above-mentioned macros are written in MATHEMATICA notebooks, which are used in MATHEMATICA analysis. Several notebooks of this type are embedded in SHIELDS to cater for different types of functions such as functions that have two, three, four or more variables and to read HADRIAN files that have different number of objects.

Data received from the HADRIAN analysis and a MATHEMATICA function fitted are evaluated for their 'fitness' in the following example.

Example:

The following 'out of reach values' were obtained by changing the position of the card slot and evaluating it with the subject 1 for each of those positions. The x, y and z co-ordinate positions are modified by adding 1000 to eliminate any negative values. 1000 was selected by studying the ATM model. The resulting values are presented below. The first three values of each data set represent x, y and z co-ordinates of the card slot and the fourth value is the 'out of reach' distance.

```
{{966.69, 1696.52, 1990.25, 0},
 {966.69, 1696.52, 2115.25, 0}, {966.69, 1696.52, 2240.25, 0},
 {966.69, 1696.52, 2365.25, 0}, {966.69, 1697.4, 2488.13, 6},
 {1154.3, 1696.55, 1990.23, 0}, {1154.26, 1696.55, 2115.23, 0},
 {1153.24, 1696.55, 2240.23, 17}, {1153.19, 1696.55, 2365.23, 0},
 {1153.12, 1697.42, 2488.11, 29}, {1392.68, 1696.55, 1990.22, 74},
 {1392.68, 1696.55, 2115.22, 74}, {1392.68, 1696.55, 2240.22, 96},
 {1392.68, 1696.55, 2365.22, 78}, {1392.69, 1697.43, 2488.11, 106}}
```

The function fitted for these data is,

$$3.35818\times 10^{10} - 1.73694\times 10^{7}\, x - 1.97942\times 10^{7}\, y + 4.03189\times 10^{-7}\, x^{2}\, y + 6.03464\, x\, y^{2} - 6.74671\times 10^{6}\, z + 8.22745\, x\, y\, z + 2.344\, y^{2}\, z - 0.00484952\, x\, y^{2}\, z$$

The following table lists the data points and the experimental value for 'out of reach' and values obtained by substituting those data points in the above equation.

Table 6.3 - Fitness of an UOF

x Co-ordinate (mm)	y Co-ordinate (mm)	z Co-ordinate (mm)	Out of reach Experimental (mm)	Out of reach From equation (mm)	| Error | (mm)
966.69	1696.52	1990.25	0	-0.007183	0.007183
966.69	1696.52	2115.25	0	-0.000004	0.000004
966.69	1696.52	2240.25	0	-0.007194	0.007194
966.69	1696.52	2365.25	0	0.014377	0.01438
966.69	1697.4	2488.13	6	6.00054	0.00054
1154.3	1696.55	1990.23	0	1.7071	1.7071
1154.26	1696.55	2115.23	0	3.45515	3.45515
1153.24	1696.55	2240.23	17	5.04671	11.95329
1153.19	1696.55	2365.23	0	6.78524	6.78524
1153.12	1696.55	2488.11	29	8.49003	20.50997
1392.68	1697.42	1990.22	74	0.000001	74
1392.68	1696.55	2115.22	74	78.7927	4.7927
1392.68	1696.55	2240.22	96	82.2027	13.7973
1392.68	1696.55	2365.22	78	85.6126	7.6126
1392.68	1697.43	2488.11	106	105.995	0.005

This shows that the fitted function very nearly fits the obtained data.

6.4.8 Optimisation

Optimisation was done to optimise the positions of the card slot and the cash dispenser by taking them as a group. In SHIELDS the interface illustrated in Figure 6.7 is provided for the SHIELDS user to enter details required for the optimisation. The user has to select a group from the list and then an object in the group to add initial values for the variables and weighting factors. Also the variables, which are to be made 'free' for the optimisation, can be specified.

The initial values are selected as the values that the variables have at the initial position of the model, i.e. the position before the optimisation. The weighting factors are to give priority to different objective functions or constraints. If a large weighting factor is specified for the users, the constraint modeller will try to satisfy the objective functions for users first and after that the constraints and vice versa. The free variables are the variables that will be changed for the optimisation. If variables are not checked then they will be fixed at the initial values and not changed. For the ATM case the x variable was fixed for the optimisation because people are free to move in x direction along the wall and to keep the overall configuration of the ATM.

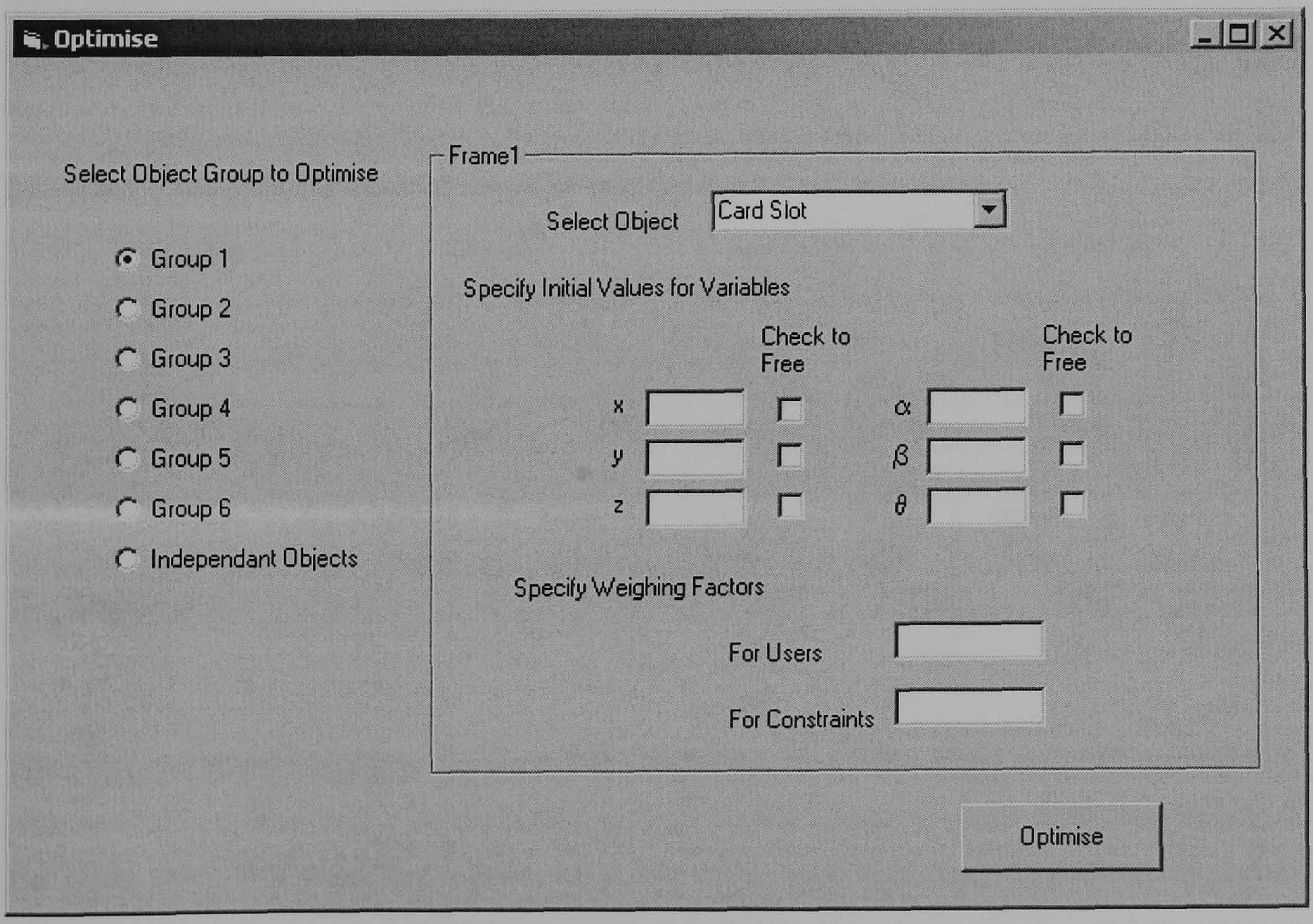


Figure 6.7 – Screen shot from SHIELDS User Interface

The ATM has only one group with two objects in it, as grouped earlier. They both have three degrees of freedom of movement each. Hence initial values for them are specified here and both weighting factors were given as 1 to give the characteristics of the users of the ATM and the constraints of the physical ATM model equal priority.

The button 'Optimise' invokes the SWORDS software and a suitable macro for the selected group will be chosen according to the number of objects in the group and the number of variables. These details were read from the user-entered data in the above screen and the necessary macro chosen according to them by VB code within SHIELDS. A set of macros for SWORDS for different scenarios are embedded within SHIELDS to cater for this requirement.

SWORDS will then use this macro to optimise the objective functions within the constraints. In other words SWORDS will find values for the variables within the constraints that would make the objective functions equal to zero. Since the objective functions given are the functions fitted for the 'out of reach' values, this would make 'out of reach' values equal to zero thus making the position reachable.

6.5 Results

SHIELDS gives out results for each object. It provides new values for the variables for each object in the group and whether or not each user of the product is able to use the object at that position. For the above case study the results obtained were given in Table 6.4.

Table 6.4 - Results obtained from optimisation

Object	x(mm)		y(mm)		z(mm)	
	Initial value	Optimal value	Initial value	Optimal value	Initial value	Optimal value
Card slot	140	140	698	696.52	1512	1005.12
Cash dispenser	37	37	698	693.201	1285	925.094
	Initial value	New value	Initial value	New value	Initial value	New value
Screen	-4	-4	698	696	1575	1068.7
Keypad	41	41	594	594	1238	732.2

The x values were the same as the initial values as they were fixed and not varied. One constraint given was that y co-ordinates should be the same to retain both the objects in the back wall. The resulting values of y are very close together. The other important constraint $80 < z_c - z_d < 140$ is also satisfied because the value of $(z_c - z_d)$ is equal to 80.026.

Resulting information about the subjects has shown that all the subjects are able to reach these positions.

6.6 Validation and Analysis

The validation was done by changing the ATM model object positions to the new values and the carrying out the HADRIAN evaluation process for reach and vision for the subjects to see if they all can use it as the results given by SHIELDS.

Since the x co-ordinate was not varied the ATM model position in x direction was not changed. For the ATM model configuration, y co-ordinates for the card slot and the cash dispenser must be the same, but the new values for these has about 4mm difference. For this, y co-ordinate of the card slot was taken for both objects, as this would not make any real difference to the model or the evaluation. Card slot and the cash dispenser are then moved to the new z co-ordinates.

To do this the whole ATM model had to be relocated to retain the configuration. This has given new positions for the screen and the keypad as well. Another possible method to find new positions for the objects, which passed the HADRIAN test initially but would need to change positions later because of the other objects, is to apply the whole optimisation process to them as well. This however is recommended only if they failed the second HADRIAN analysis.

All the objects are taken for the HADRIAN evaluation for validation. A summary of the results is given in the Table 6.5. The detailed results file is given in appendix 1.

Table 6.5 - Hadrian Analysis Results

HADRIAN Results Sheet

Subjects	Screen	Card Slot		Keypad		Cash dispenser	
	Look	Look	Reach	Look	Reach	Look	Reach
Subject 11	success	success	success	success	success	success	success
Subject 12	success	success	success	success	success	success	success
Subject 27	success	success	success	success	success	success	success
Subject 28	success	success	success	success	success	success	success
Subject 40	success	success	success	success	success	success	success
Subject 41	success	success	success	success	success	success	success
Subject 47	success	success	success	success	success	success	success
Subject 54	success	success	success	success	success	success	success
Subject 97	success	success	success	success	success	success	success
Subject 98	success	success	success	success	success	success	success

Percentage Accommodation

	Look	Reach
Screen	100%	n/a
Card Slot	100%	100%
Keypad	100%	100%
Cash dispenser	100%	100%

This shows that the SHIELDS results are valid for the ATM model.

6.7 Conclusions

Although this case study only contained one object group and two interdependent objects in the group it has proven that SHIELDS works and gives valid results. It also proved that the links between the software within SHIELDS are sound. The case study also tested the three hypotheses made in the objectives. The first hypothesis states that 'If a user is unable to use a product or workplace because for example, it is out of reach, changing the parameters of that product or workplace and evaluating it with a computer model of the user to obtain a value for this failure, for example the out of reach distance, for each of these positions, will generate a path for this inability and that path can be mapped into a mathematical expression.' This was tested in the section 6.4.7 under 'function fitting' and the results there provide evidence for the truth of the hypothesis.

The second hypothesis states that 'All the factors required for the optimisation of physical aspects of a design concerning the users and the product or workplaces can be expressed as mathematical functions enabling them to be used in an optimisation process with any other constraints that affect the product'. This hypothesis was tested in this case study by considering the necessary factors of the ATM to optimise its physical aspects. All the necessary physical aspects were expressed as mathematical formulae and were used successfully in the optimisation process with the other constraints.

The third hypothesis states that 'The Inclusive Design Synthesis problem can be structured in such a way that it can be implemented in a software system to ensure it being evaluated and practically formulated in an optimisation process and then being able to solve it'. The successful results of the above case study are the proof for this hypothesis. These hypotheses will be further tested in the next chapter.

The results have also shown that SHIELDS is capable of handling at least two dependent objects. The most important result with regard to the Inclusive Design concept implementation however is SHIELDS capability of incorporating the users of products in the design optimisation process as done with the user centred objective functions.

6.8 Summary

This chapter has presented a case study to test the hypotheses made earlier and also to test the functionality of SHIELDS. The results obtained have shown that the hypotheses were tested true and that SHIELDS is functioning according to plan. It has also shown that the method developed to tackle the design synthesis problem is valid. This case study has the limitation of the number of objects in a group and also the number of groups in the workplace. In other words it is somewhat lacking in complexity. This will be dealt with in the next chapter.

Chapter 7

The Kitchen Workplace Case Study

7.1 Chapter Overview

This chapter discusses a case study involving a kitchen workplace. Most of the main objects in a kitchen are considered for the optimisation. The methodology carried out in the process of evaluation of this case study is described. This case study represents a real life design problem involving a large number of variables that each has several degrees of freedom. By conducting this case study SHIELDS ability to handle a complex design problem was analysed. Furthermore the method developed to achieve the inclusivity in designs by design synthesis is tested again.

7.2 Description of the Case Study

If there is one workplace in the world that needs no description, it is the kitchen. All over the world in almost every house there is a place to cook. The size and the objects in these places may vary, but the main functions remain the same. Traditionally the kitchen belonged to the woman or more to the point the woman belonged to the kitchen. However with more and more women going off to work and men learning the pleasures of cooking, the kitchen is becoming a place for everyone. Even the elderly people, who increasingly live by themselves, need to use the kitchen at least once a day. This provides a very good reason to include all in the kitchen.

7.2.1 Background

Cooking and kitchen goes back a long way into history. First cooking was done outside on an open fire. Then cooking moved indoors with the people as the civilisations blossomed. As the houses became larger, a special place for cooking was assigned. Although there still are dwellings in the world where the cooking is done in a corner of the living space, a separate room for cooking was found in rich households even in early civilisations. For example the kitchen shown in Figure 7.1 is a reproduction of a kitchen in 62 A.D. in Rome (www - Pompeii Gateway). A small fire on the platform (on the right) would be used for cooking, with pots sitting above the fire on small tripods. Interestingly it contains many of the features in the modern kitchen shown in Figure 7.2 including a work surface, shelves, food and hanging utensils.

Figure 7.1 - Reproduction of a Roman kitchen (www – Pompeii Gateway)

Figure 7.2 – A modern kitchen (A catalogue picture)

The main purpose of the kitchen is to prepare and cook food. However, in many households, dining and informal entertaining is also carried out in the kitchen. Therefore the kitchen must contain a place to wash food, prepare it and cook it as well as a place to store the food and a place to eat it. Manufacture of this multifunctional kitchen in today's world is a multimillion-pound industry, which has a huge market.

7.2.2 Importance of the Kitchen Case Study with regard to the Project Presented in this Thesis

The importance of the kitchen is seen from the fact that almost every house in the world has one. Almost everyone in the house uses the kitchen at least occasionally. Preparing food for oneself is an important part of being independent. This fact was shown clearly in the research done by the 'design for all' project group in Loughborough University (Gyi, 2000). They report that more than half the elderly and disabled people surveyed have said that cooking for themselves or for friends and family comes top in the list of things they would like to be able to do. Cooking was considered to be one of the most important activities of daily living, which are important to the well being, and independence of all people in the society.

Therefore the kitchen workplace provides an ideal opportunity to test a workplace that is important to the whole population.

With regard to the design optimisation method developed in this project, the kitchen provides the setting to test it with the people of all kinds of abilities and it also provide the facilities to test the software. The kitchen workplace satisfies all these in the following ways.

- The kitchen contains a large number of objects such as the cooker, the work surface, the shelves, the microwave, the fridge etc. These objects while they can have freedom to move for optimisation, constrain each other by the limited space around the kitchen. These can be used to test the proposed methods of decomposition of the workplace, dependent objects, HADRIAN analysis and the optimisation.
- The kitchen workplace provides the necessary complexity with regard to the number of objects and the dependencies of the objects on each other and the constraints imposed. These can be used to test the functionality of the software and limits of the proposed method.
- People with all abilities and ages need to use the kitchen. This gives the case study the necessary justification to use it to achieve inclusivity. The kitchen is an important part of the daily life, which makes it a worthwhile subject for the case study.
- Since people need to move around the kitchen and fit into the workplace, this also provides opportunities to test the ability of the software to accommodate fit as well as reach and vision.

7.2.3 Tasks performed by people when using a Kitchen

The main task people perform in the kitchen is preparing meals. To prepare a meal the tasks people perform in a kitchen are numerous and varied. They range from washing, and cutting to lifting and carrying heavy or hot objects. These tasks involve various objects in the kitchen. For the purposes of this case study a general kitchen with the shelves, the working surface, the cooker, which includes the oven, the fridge, the clock and the sink, is considered.

The tasks people perform with respect to each of these objects in order to perform the main task, which is to prepare a meal, in general are

- Get food from the fridge
- Wash food in the sink
- Get pots and pans from the shelves
- Prepare food on the work surface
- Cook on the hob
- Put food in the oven
- Move between the objects such as move from the fridge to the sink etc.
- Look at the clock etc.

These tasks are explained in detail in the section 7.4.2.

When specifying these tasks only the physical aspects of the users were considered and their strength and other characteristics were not considered. Being able to carry out any of these tasks depend on the users physical characteristics and capabilities as well as the position and the dimensions of the objects. SHIELDS can be used to find better positions for these objects to maximise user accommodation. Many of the dimensions for modern kitchens depend on the products used in them. For example if standard items such as cookers and fridges are used in the kitchen, they might determine the height of the work surfaces due to the considerations of the aesthetics of the workplace.

7.3 Objectives of the Case Study

7.3.1 To test the hypotheses made in chapter 1

- The first hypothesis states that the when users failed to complete a task, by obtaining the 'failure values' it is possible to generate a path for this inability and that path can be mapped into a mathematical expression.
- The second hypothesis states that the physical aspects concerning the users and the design as well as the constraints can be expressed in mathematical terms in order to use them in an optimisation process.

- The third hypothesis states that the Inclusive Design problem can be formulated in such a way as to be able to implement in a software system to be solved in an optimisation process.

7.3.2 To find a better layout for the kitchen design to maximise user accommodation

7.3.3 To determine SHIELDS capability to optimise several interdependent objects with various degrees of freedom

7.3.4 To determine SHIELDS capability to incorporate characteristics of the users of products or workplaces in the design process as well as its capability of evaluating and optimising reach, fit and vision.

7.4 Methodology

The new software SHIELDS optimisation process follows the steps below (as previously described in section 6.4).

- Model building
- HADRIAN evaluation
- Components/objects selection for optimisation (decomposition)
- Object grouping according to the task
- Constraint selection for each of the degrees of freedom for every object as well as the selection of relative constraints
- HADRIAN analysis to obtain failure values
- Function fitting
- Optimisation using SWORDS software

7.4.1 Model Building

There are four main types of modern kitchens. These are the Galley shape, the Two-way Galley shape (Figure 7.3), L shape (Figure 7.3), the U shape (Figure 7.3) and the Island named according to the layout of the objects in it. As mentioned in section 7.2.3 the kitchen model used in the case study consists of following objects in an L shaped layout as shown in Figure 7.4.

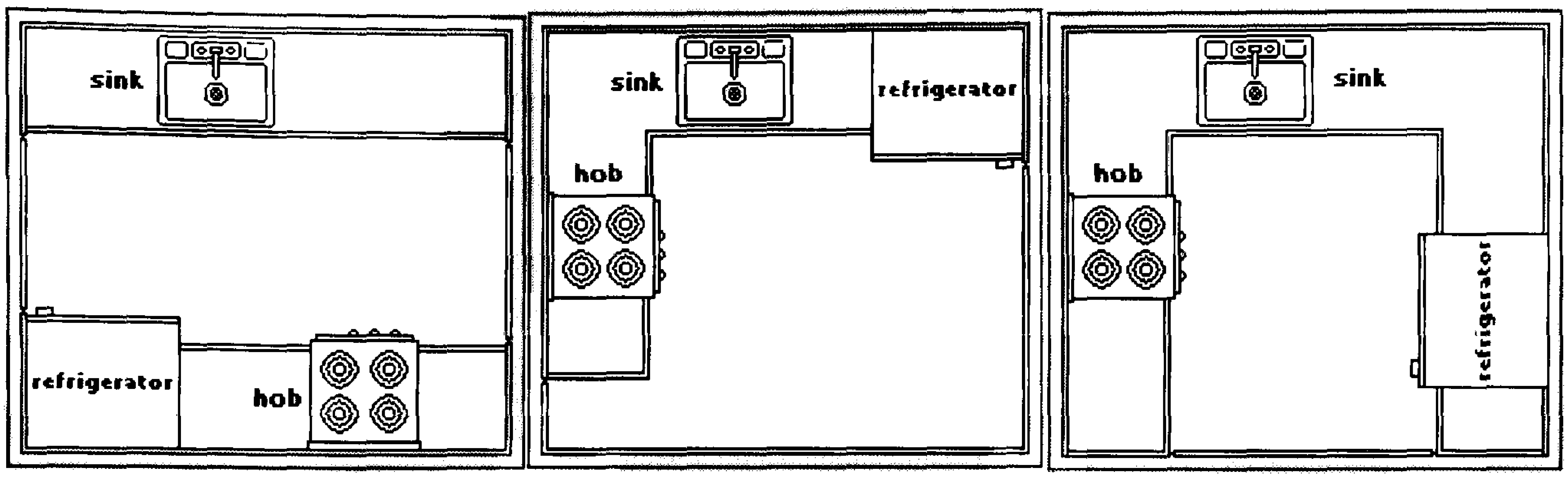


Figure 7.3 – Two way Galley layout, L - shaped layout and U – shaped layout (www – kitchen buyer's guide)

- Shelves
- Sink
- Cooker, which includes the oven
- Working surface
- Clock
- Fridge
- Tap

An effort has been taken to maintain the 'work triangle' showing in Figure 7.4 the corners of which must contain the fridge, the sink and the cooker. In other words the work triangle in a kitchen is based on the concept that a well-balanced and well-designed kitchen should incorporate a separate area for cooking, food preparation and a wet area. For the greatest efficiency the total length of the three sides of the triangle should be between 3600mm and 6600mm (Rowe, 2002). The dimensions of the working surface, the sink, cooker and the shelves are considered to be non-standard. The fridge and the clock are standard items with fixed dimensions and only the positions of them can be changed for the optimisation.

Usually kitchen workplaces contain cupboards below the work surface and the sink. But in this model they were omitted to accommodate the wheelchair users. The design changes such as this has to be done by the designer at the conceptual stage when they consider Inclusive Design concepts and try to achieve them.

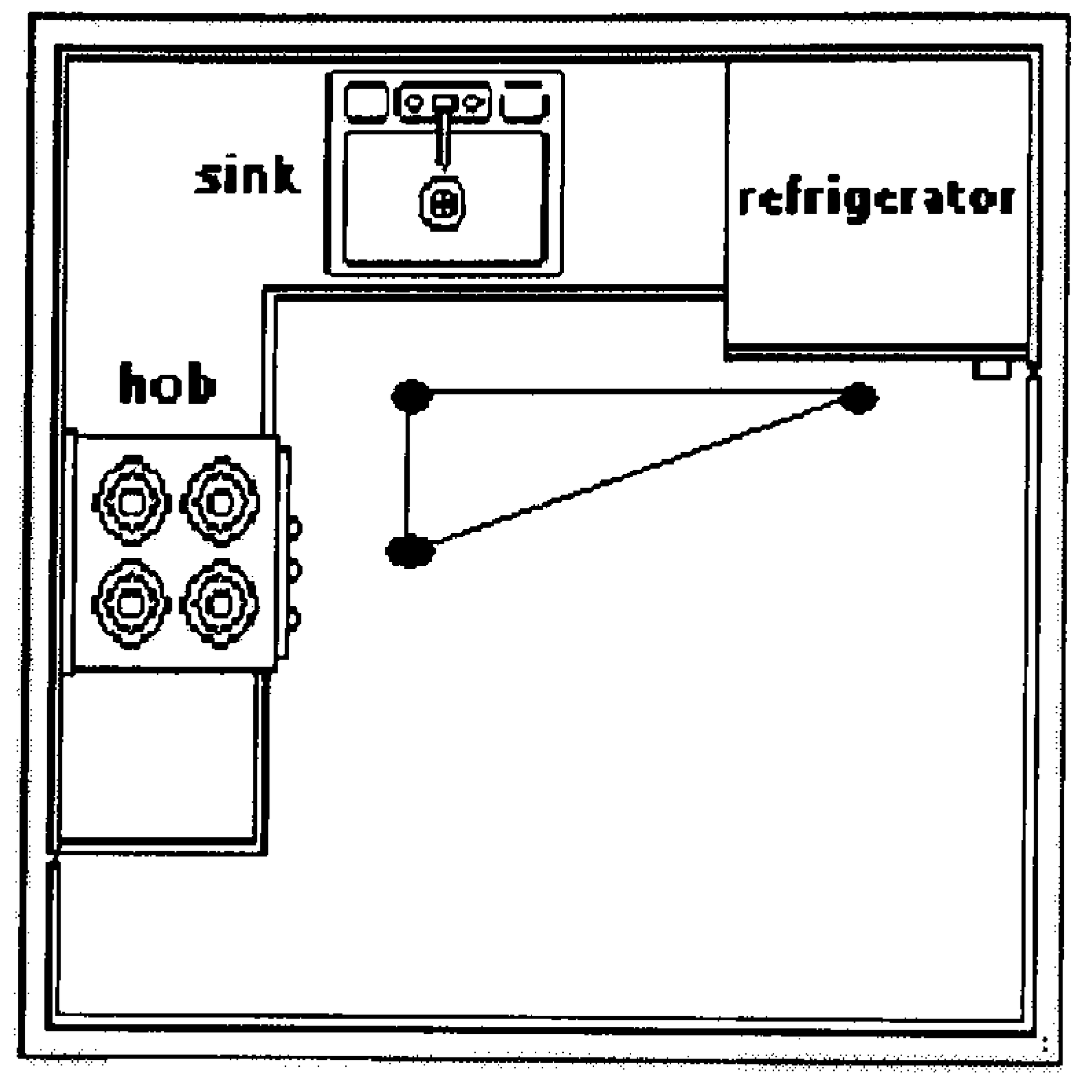


Figure 7.4 – General layout of the kitchen showing the working triangle

The dimensions used to build the kitchen model were obtained from an existing kitchen. These dimensions are provided in Figure 7.5 and Figure 7.6 . The model was built using SAMMIE PC version. Only the functional dimensions and features are used in the model and details that are not required for the functionality were left out.

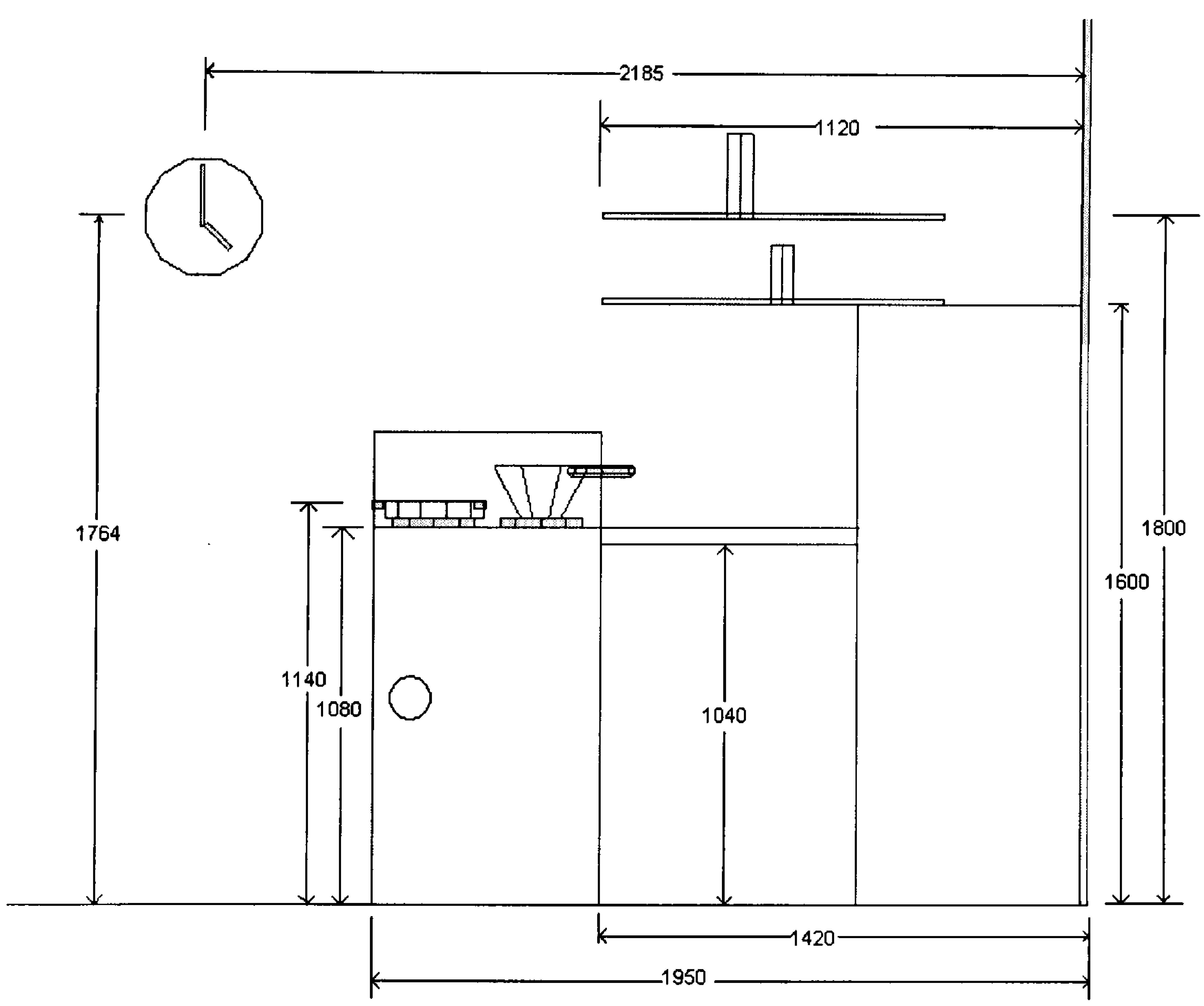


Figure 7.5 - Kitchen dimensions: Front Elevation

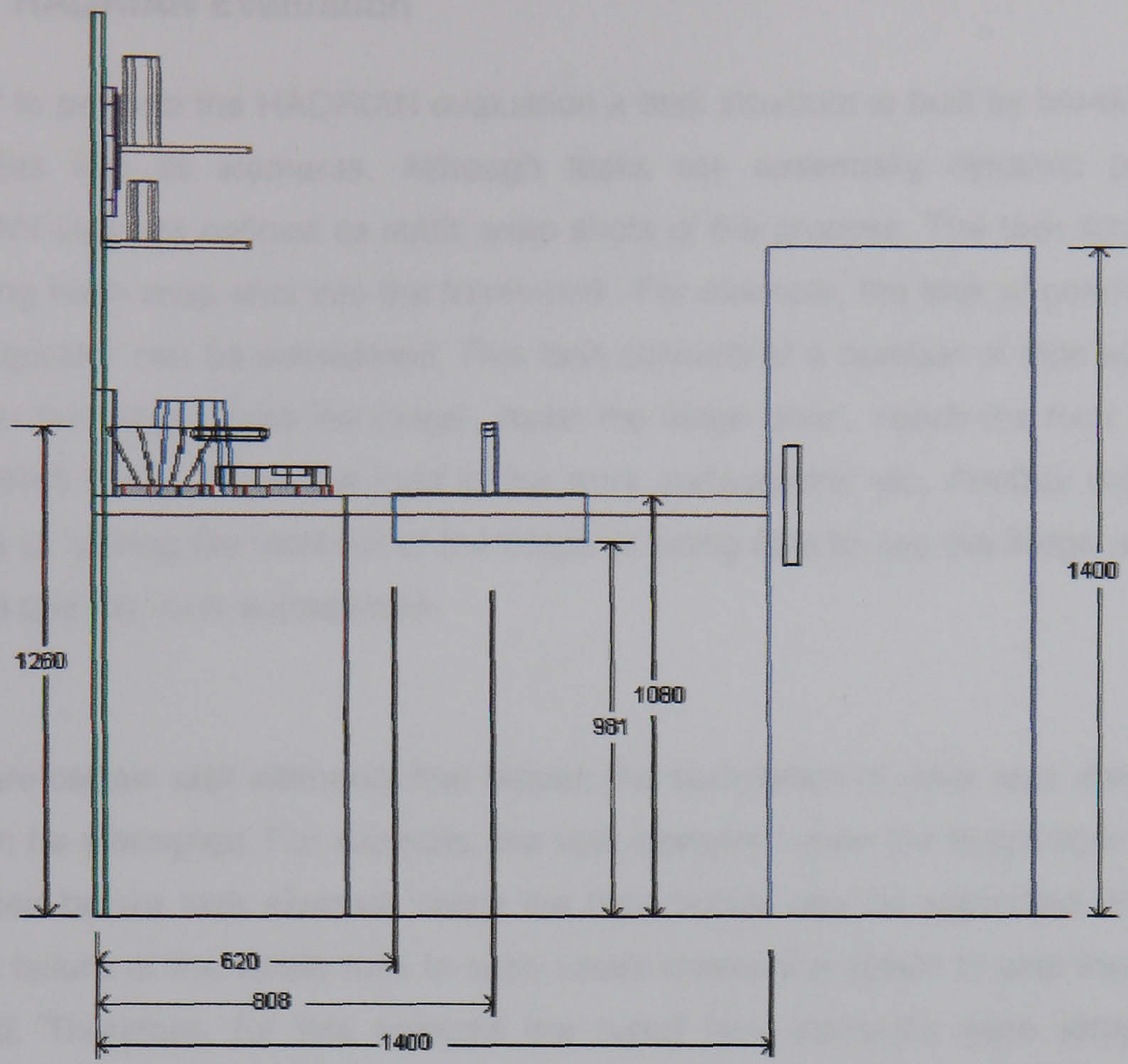


Figure 7.6 - Kitchen dimensions: End Elevation

Figure 7.7 shows the model of the kitchen built in SAMMIE.

Figure 7.7 – The kitchen model built on SAMMIE

7.4.2 HADRIAN Evaluation

In order to perform the HADRIAN evaluation a task structure is built by breaking down the main task into its elements. Although tasks are essentially dynamic processes, in HADRIAN they are defined as static snap shots of the process. The task structure is built by adding each snap shot into the framework. For example, the task of getting food out of the refrigerator can be considered. This task consists of a number of task elements such as 'go to the fridge', 'face the fridge', 'open the fridge door', 'reach the food element with the right/left hand', 'move the food to the work surface/sink' etc. Another criterion for the success of 'getting the food out of the fridge' is being able to see the fridge door and then the food and the work surface/sink.

There are certain task elements that require the completion of other task elements before they can be attempted. For example, the task element ' open the fridge door' needs to be completed before task element 'reach the food inside' can be attempted. HADRIAN will flag the failure of the whole task in such cases unless the option to skip the failures was selected. Therefore, for this analysis the failed task elements were skipped and the evaluation was moved to the next step to carry out all the task evaluation process. This will ensure that the data is collected on all the task elements and thus provides a full list of task element failures and successes rather than the first failure only.

The main task that is being tested in this case study is 'preparing a meal'. The tasks associated with preparing a meal are assumed to be the tasks described below. The detailed structure of these tasks and their associated task elements are also described. This is the structure that has been used in the HADRIAN evaluation.

Overall Task: Prepare a meal

In order to perform the overall task successfully, users must be able to perform the following tasks and tasks elements within the tasks.

Task 1: Get food from the fridge

Task element 1: Move in front of the fridge

Task element 2: Turn toward fridge

Task element 3: View fridge door

Task element 4: Reach fridge door (with right/left hand - thumb tip)

Task element 5: View food element

Task element 6: Reach food element (with right/left hand – palm grip)

Task 2: Wash food in sink

Task element 1: Move in front of the sink

Task element 2: Turn towards sink

Task element 3: View bottom of the sink

Task element 4: Reach bottom of the sink (with both hands – thumb tip)

Task element 5: View the tap

Task element 6: Reach the tap (with right/left hand – thumb tip)

Task element 7: Turn towards clock

Task element 8: View clock

Task 3: Get pots and pans from shelves

Task element 1: Move closer to the shelves

Task element 2: Turn towards shelves

Task element 3: View shelf 1

Task element 4: View the object on shelf 1

Task element 5: Reach object on shelf 1 (with right/left hand – thumb tip)

Task element 6: View shelf 2

Task element 7: View object on shelf 2

Task element 8: Reach object of shelf 2 (with right/left hand – thumb tip)

Task 4: Prepare food on the work surface

Task element 1: Move closer to the middle of the work surface

Task element 2: Turn towards work surface

Task element 3: View work surface

Task element 4: Reach work surface (with right/left hand – flat palm)

Task element 5: Reach work surface (with the other hand – palm grip)

Task element 6: Turn towards clock

Task element 7: View clock

Task 5: Cook on the hob

Task element 1: Move near the cooker

Task element 2: Turn towards hobs

Task element 3: View back hob with pan 2 on

Task element 4: Reach pan 2 (with right/left hand – thumb tip)

Task element 5: Turn towards clock

Task element 6: View clock

Task 6: Put food in the oven

Task element 1: Move closer to oven (if not there already)

Task element 2: Turn towards oven

Task element 3: View tray in the oven

Task element 4: Reach tray in the oven (with both hands – palm grip)

Task element 5: Turn towards clock

Task element 6: View clock

These tasks are then defined to HADRIAN system via HADRIAN task builder. A part of the task structure built on HADRIAN is shown in the left of the Figure 7.8.

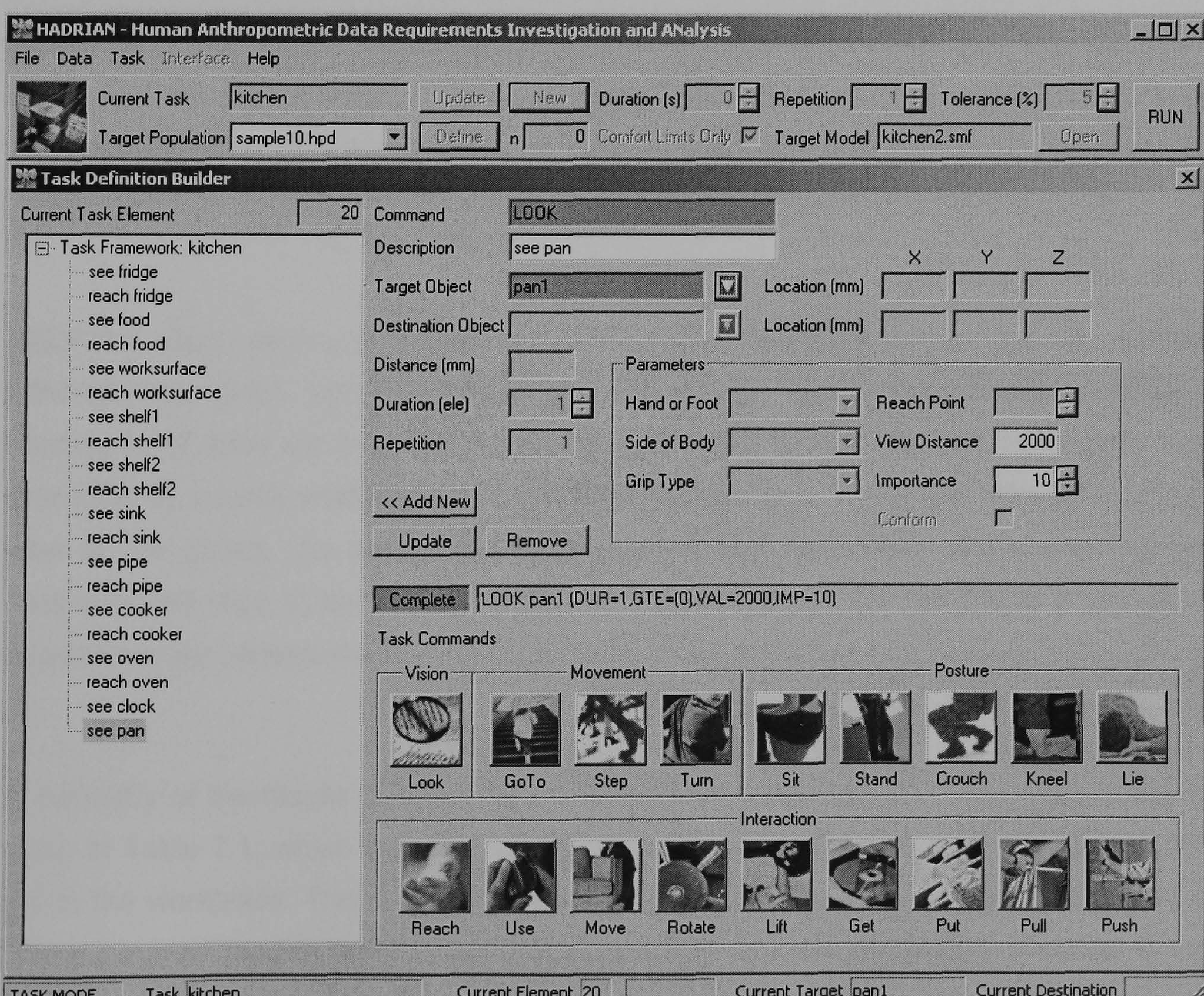


Figure 7.8 – HADRIAN Task Builder

The sample of users selected for this case study is the same as that of the ATM case study.

Interference between the solid objects and the human model is not tested in the HADRIAN evaluation. However this is very important when considering the users ability to reach objects because when interference is not considered the model can reach through objects and report a success whereas in real life this is not possible. To overcome this problem, additional objects were placed in the path of reach and the model has to reach through them to successfully complete the task without interference.

For example, testing of the depth of the sink has been a problem because the models that were in wheelchairs were reaching the bottom of the sink through its wall. To overcome this a small object was placed above the sink for these models to reach. It is assumed that if they can reach that height above it, they will be able to reach the bottom of the sink. The height of that object was determined by analysing the upper arm and forearm lengths of the models and the depth of the sink. For the standing models the depth was tested by reaching the bottom of the sink. A similar strategy was used for the reach test of the oven work surface and cooker/hobs.

In the case of the cooker the hobs at the back of the cooker were used to test reach and vision. It is assumed that if the users can reach the hobs at the back of the cooker then they are able to reach the other hobs as well. To test the reach and vision capability with respect to the shelves, two objects were put on them for the users to see and reach.

HADRIAN vision testing is based on SAMMIE viewing capabilities of the man model. Although this gives accurate results for vision with respect to humans and their constraints, it does not consider the solids and tends to look through them. This was overcome by visually studying the HADRIAN analysis. Since HADRIAN shows the man's view of the object, the author was able to view and note down when solid objects obstructed the view of the models. However this process will be impossible when larger populations are considered.

A summary of the results obtained by this HADRIAN evaluation on the existing model is given in Table 7.1, which includes the percentage accommodation for each task carried out in the workplace. The detailed results are given in appendix 2. A task is declared a failure if human models failed to perform at least one task element that is essential to the completion of the task. The user accommodation was calculated based on the success of tasks.

Table 7.1 - Tasks and user accommodation

Task element	subjects (success = 1, failure = 0)										User accommodation	Importance to the overall task
	11	12	27	28	40	41	47	54	97	98		
Move in front of fridge	1	1	1	1	1	1	1	1	1	1	100%	necessary
Turn towards fridge	1	1	1	1	1	1	1	1	1	1	100%	necessary
View fridge door	1	1	1	1	1	1	1	1	1	1	100%	necessary
Reach fridge door	1	1	1	1	1	1	1	1	1	1	100%	necessary
View food element	1	1	1	1	1	1	1	1	1	1	100%	necessary
Reach food element	1	1	1	1	1	1	1	1	1	1	100%	necessary
Move in front of sink	1	1	1	1	1	1	1	1	1	1	100%	necessary
Turn towards sink	1	1	1	1	1	1	1	1	1	1	100%	necessary
View bottom of sink	1	1	1	1	0	0	1	1	1	1	80%	necessary
Reach bottom of sink	1	1	1	1	0	0	1	1	1	0	70%	necessary
View tap	1	1	1	1	1	1	1	1	1	1	100%	necessary
Reach tap	1	1	1	1	0	0	1	1	1	0	70%	necessary
Turn towards clock	1	1	1	1	1	1	1	1	1	1	100%	not a must
View clock	1	1	1	1	1	1	1	1	1	1	100%	not a must
Move closer to shelves	1	1	1	1	1	1	1	1	1	1	100%	necessary
Turn towards shelves	1	1	1	1	1	1	1	1	1	1	100%	necessary
View shelf 1	1	1	1	1	1	1	1	1	1	1	100%	necessary
View object on shelf 1	1	1	1	0	0	0	1	1	1	0	60%	necessary
Reach object on shelf 1	0	0	0	0	0	0	1	1	1	0	30%	necessary
View shelf 2	1	1	1	1	1	1	1	1	1	1	100%	necessary
View object on shelf 2	1	1	1	1	0	0	1	1	1	1	80%	necessary
Reach object on shelf 2	0	1	1	1	0	0	1	1	1	0	60%	necessary
Move to work surface	1	1	1	1	1	1	1	1	1	1	100%	necessary
Turn to work surface	1	1	1	1	1	1	1	1	1	1	100%	necessary
View work surface	1	1	1	1	1	1	1	1	1	1	100%	necessary
Reach work surface	1	1	1	1	0	0	1	1	1	1	80%	necessary
Turn towards clock	1	1	1	1	1	1	1	1	1	1	100%	not a must
View clock	1	1	1	1	1	1	1	1	1	1	100%	not a must
Move to cooker	1	1	1	1	1	1	1	1	1	1	100%	necessary
Turn towards cooker	1	1	1	1	1	1	1	1	1	1	100%	necessary
View back hob/pan 2	1	1	1	1	0	1	1	1	1	1	90%	necessary
Reach pan 2	0	0	0	0	0	0	1	1	1	0	30%	necessary
Turn towards clock	1	1	1	1	1	1	1	1	1	1	100%	not a must
View clock	1	1	1	1	1	1	1	1	1	1	100%	not a must
Move to oven	1	1	1	1	1	1	1	1	1	1	100%	necessary
Turn towards oven	1	1	1	1	1	1	1	1	1	1	100%	necessary
View tray	1	1	1	1	1	1	1	1	1	1	100%	necessary
Reach tray	1	1	1	1	0	0	1	1	1	1	80%	necessary
Turn towards clock	1	1	1	1	1	1	1	1	1	1	100%	not a must
View clock	1	1	1	1	1	1	1	1	1	1	100%	not a must

The above table shows the success or failure of each individual user against task elements. It shows that the subjects who have failed most are subject 40 and subject 41. Subjects that were able to perform most tasks were the subjects 47 and 54. By analysing the user profile given in the ATM case study, it can be seen that subjects 40 and 41 are the wheelchair users and subjects 47 and 54 are young able people. These facts show that knowing the individual assists the designer to predict the accessibility by that person among other things.

The task elements that must be completed in order to complete the overall task of preparing a meal are specified as 'necessary' task elements. The other task elements that are specified but do not directly affect the overall task success are given as 'not a must' tasks. Therefore the user accommodation for the overall task is the least percentage of user accommodation in a 'necessary' task element. By analysing the above table, the user accommodation of the overall task is shown as 30%. This means that only 30% of the individuals who attempted to prepare a meal in the above kitchen were able to do it. The task of SHIELDS is now to increase this user accommodation, if possible to 100% to enable all the individuals to use the kitchen by optimising the kitchen workplace.

7.4.3 Decomposition and Grouping

The shelves, the sink and the work surface, the cooker and the oven in the kitchen workplace can be moved and resized to allow more users to use them. The clock and the fridge are assumed to be standard models, which can only be repositioned. The total kitchen model is thus decomposed into those objects. Then each of them was analysed with regard to the tasks the users perform with those objects.

The functional decomposition of the workplace is shown in the Figure 7.9 with the associated objects. The basic tasks the users have to perform to achieve the success in the main task of preparing a meal are thus defined. The order each task has to be performed is also illustrated in the figure. The order of the tasks is selected on the basis of the typical routine carried out in preparing a meal.

Although the order of the tasks and the objects used for that particular task may vary from user to user this will not affect the usability of the objects. Hence it is assumed that this will not affect the user accommodation with regard to the object position and the size. Another fact to notice at this point is that some objects e.g. the work surface appear more than once in the tasks. This makes the analysis more complex with regard to the interdependency.

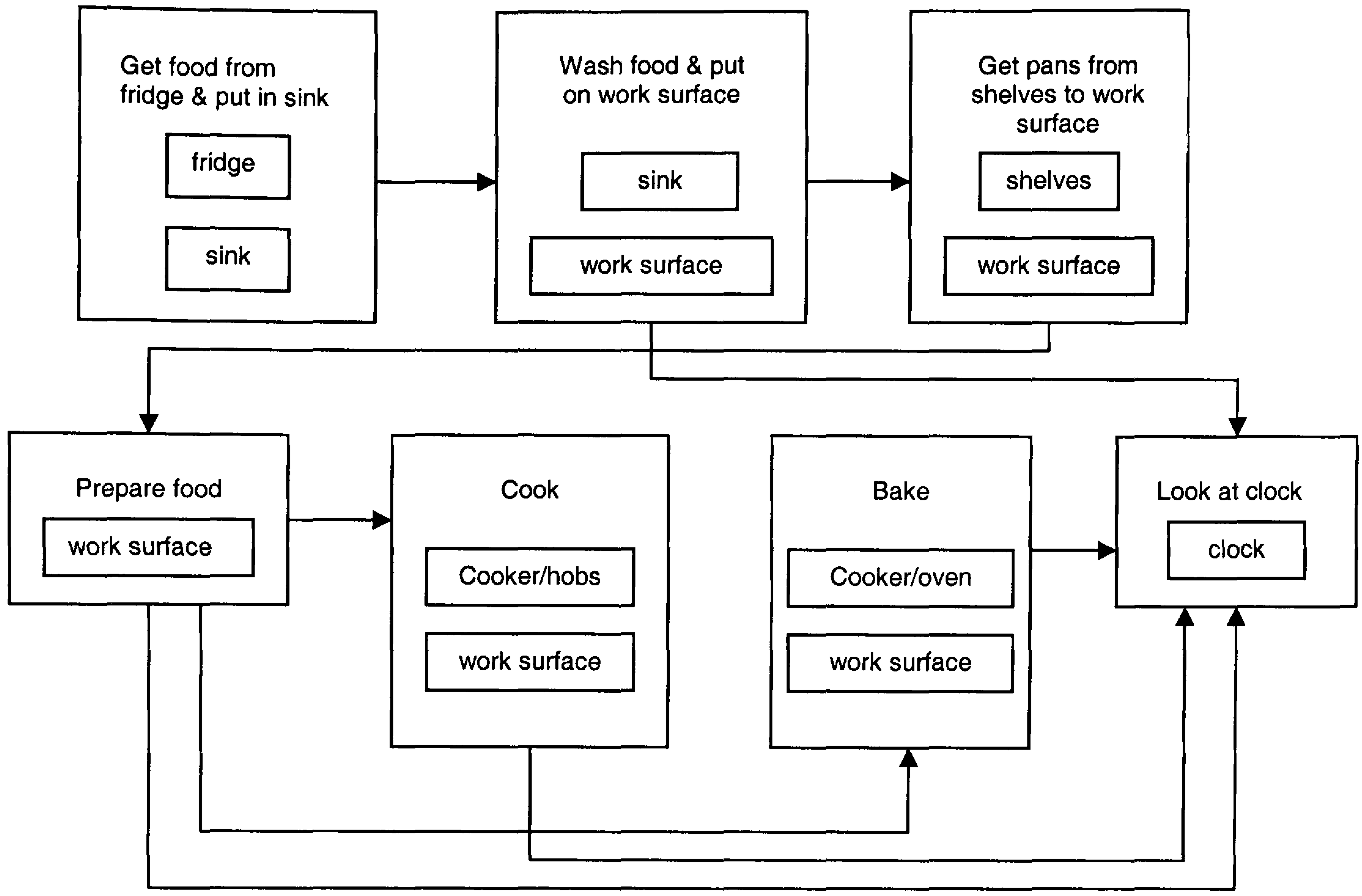


Figure 7.9 - Tasks and associated objects

The next step in the analysis process is to identify dependent objects. These are the objects for which positions or size will affect each other. For this it is necessary to identify the degree of freedom of each object. The Table 7.2 provides this information. Independent objects are those objects that are not affected by the size or position of other objects.

Table 7.2- Degrees of freedom of the objects

Object	Degrees of Freedom
Cooker	y, z
Oven	y, z
shelf 1	y, z
shelf 2	y, z
fridge	x, z
sink	x, y, z
tap	x, y, z
work surface	y, z
clock	y, z

Based on this information and also by analysing the layout of the workplace and the tasks carried out, the objects are grouped as illustrated in Table 7.3

Table 7.3 - Object Grouping

Group
Cooker
Oven
work surface
Sink
Tap
shelf 1
shelf 2
Fridge
Clock

7.4.4 Variables and Constraints Selection

Variables of the objects are those given in the Table 7.2. Constraints for each of these variables are selected by studying the workplace and also considering the working triangle specifications. The nature of the workplace with its many objects presents large number of constraints with regard to the objects. Many of these constraints involve the size or the position of one or more related objects. These constraints are described below.

Figure 7.5 and Figure 7.6 illustrate the front and end elevations of the kitchen workplace. These diagrams are used only to define the constraints.

The clock in the kitchen must be seen from near the cooker, the work surface and the sink, according the tasks specified in Figure 7.9. The movement of the clock is restricted in the y direction by the shelves. If the position of the clock is (x_8, y_8, z_8) the position of shelf 1 (upper shelf) is (x_5, y_5, z_5) and the position of shelf 2 is (x_6, y_6, z_6), this restriction can be expressed as

$$y_8 > y_5 \qquad \text{(a)}$$

$$y_8 > y_6 \qquad \text{(b)}$$

The shelves on the other hand, the heights of which depend on each other to provide a space in between for objects, are restricted by the position of the clock and the wall in the y direction and the work surface on the z direction. If the position of the work surface is (x_7, y_7, z_7) these limitations can be expressed as

$$(z_5 - z_6) \geq a \qquad \text{(c)}$$

$$0 < y_5 < y_8 \qquad \text{(d)}$$

$$0 < y_6 < y_8 \qquad \text{(e)}$$

$$z_6 - (z_7 + b) > c \tag{f}$$

Where a, b and c are height of the highest object that can be put on shelf 2, the thickness of the work surface and height of the space that need to be left between the work surface and the shelf 2.

The height of the work surface should be the same as the cooker and the sink for aesthetic considerations of the workplace. If the position of the cooker is (x_3, y_3, z_3), the height of the cooker is h_1, the position of the sink is (x_4, y_4, z_4) and the depth of the sink is d_1, these constraints can be given as

$$(z_3 + h_1) = z_7 = (z_4 + d_1) \tag{g}$$

Although the length and the width of the cooker and the oven are not allowed to change for optimisation, to retain the overall shape the heights of the oven and the hobs can be varied. These heights depend on each other for functionality of the oven. If the position of the oven is (x_1, y_1, z_1) and the largest object that can be put in the oven has a height of h_2, this can be written as

$$(z_1 + h_2) < (z_3 + h_1) \tag{h}$$

The position of the sink must be considered in two respects. Firstly, the users must be able to reach the bottom of the sink and see the objects in the sink. This depends on its height and secondly for the users to reach the tap the width of the sink must be considered. The width and the height of the sink are restricted by the functionality of the sink. In this case the width of the sink was also taken as a variable for the optimisation. The tap has to be seen and reached by the users and it is position is constrained so that it must be on an edge, except the front edge, of the sink.

To express these constraints in a mathematical form the following variables are defined.

Width of the sink = w_1

Length of the sink = l_1

The dimensions of the largest item put in the sink:

height = h_3, length = l_2, width = w_2

Position of the tap = (x_2, y_2, z_2)

Therefore the constraints associated with the sink and the tap are

$$y_2 < y_4 \tag{i}$$

$$(z_2 - z_4) = d_1 \tag{j}$$

$$x_4 \le x_2 \le (x_4 + l_1) \tag{k}$$

$$\text{If } x_2 = x_4 \text{ then } w_2 < (y_2 - y_4) < w_1 \tag{l}$$

$$\text{If } x_2 = (x_4 + l_1) \text{ then } w_2 < (y_2 - y_4) < w_1 \tag{m}$$

$$\text{Else if } x_4 < x_2 < (x_4 - l_1) \text{ then } w_2 < (y_2 - y_4) = w_1 \tag{n}$$

$$(x_2 - x_4) > l_2 \tag{o}$$

The positions of most of the objects are restricted by the limits placed on the working triangle between the cooker, the fridge and the sink. If the total length of the three sides of the working triangle is t, the width of the cooker is w_3, length of the fridge is l_4 and the position of the fridge is (x_9, y_9, z_9) then

$$t = \{(y_3 - ½ * w_3) - y_4\} + \{(x_9 + ½ * l_4) - (x_4 + ½ * l_2)\} + (\{(y_3 - ½ * w_3) - y_4\}^2 + \{(x_9 + ½ * l_4) - (x_4 + ½ * l_2)\}^2)^{½}$$

To be within the given guidelines for working triangle mentioned in section 7.4.1

$$3600 \leq t \leq 6600 \tag{p}$$

Each of these constraints was considered in the optimisation process together with the minimum and maximum values of the variables.

7.4.5 HADRIAN analysis for the Objects for Optimisation

Being a prototype software tool, HADRIAN has functional limitations when considering a workplace that has many objects that need to be tested such as the kitchen used in this case study. Therefore the author had to perform some manual programming and hard coding to get around these limitations. Since HADRIAN is still in development and these limitations will get resolved with time, the limitations or the programming carried out to overcome them are not included in the case study. The limitations are only functional and did not interfere with HADRIAN's ability to consider a large number of users in the evaluation.

To get the data points to fit functions to obtain the user centred objective functions, all objects in the Table 7.3 were analysed by changing their positions and evaluating with all the users. This analysis has given 10 data points for each user per object for reach and fit.

Since the vision was tested manually to overcome the limitation of models looking through the solid objects, 'out of sight' distances could not be obtained. For this a binary system of assigning one if 'out of sight' or zero if the object can be seen was used.

7.4.6 Function Fitting

Functions are fitted for the data points obtained by HADRIAN analysis. These functions represent the path for the 'out of reach' distances for each user per object. For example, if a user is unable to reach the bottom of the sink for certain positions these 'out of reach' distances are mapped into a mathematical formula against the various positions of the sink. These functions are written for vision as well.

Therefore each user will have two user centred objective functions, one for 'out of reach' and one for 'out of sight' for a single object. Altogether there are 20 user centred objective functions per object. Two examples of the functions fitted this way are given below and all of these functions are listed in Appendix 2.

This is the function fitted for subject 1 to reach the sink

$$1.6422 \times 10^{6} - 301.506\,x - 434.786\,y + \frac{103\,x y^{2}}{500000} - 112.468\,z + \frac{289\,x y z}{1000000} + 8.7441 \times 10^{-6} y^{2} z - 1.2063 \times 10^{-9} x y^{2} z$$

This is the function fitted for the subject 4 to reach the oven

$$-1.3215 \times 10^{6} + 176.793\,x + 720.919\,y - \frac{529\,x y^{2}}{1000000} + 182.735\,z - \frac{573\,x y z}{1000000} + \frac{247\,y^{2} z}{500000} + 2.8144 \times 10^{-8} x y^{2} z$$

These functions were fitted to the mathematical model defined in chapter 4 and the co-efficient that have a value less than 10^{-9} were omitted.

Usually the position of the user remained stationary when the position of the object changed to find these distances. Although the co-ordinates of the model were not changed the human model was allowed to change posture to achieve tasks.

The clock in the kitchen provides a unique example for this analysis because it has to be viewed from several different locations by each user. In this case for each location of a single user a different function is fitted and they are all considered in the optimisation.

7.4.7 Optimisation

There are various physical aspects to consider in the optimisation. For example, the heights of the hobs on the cooker must be low enough for wheelchair users and high enough for tall people with bad backs. That is, if the height of the cooker was increased for the benefit of the users with bad backs, it will exclude the wheelchair users. These people with 'bad backs' or people who have trouble bending their backs beyond a certain limit are represented in the HADRIAN analysis by the application of joint constraints for the spine. These factors require finding an optimum height to maximise the user accommodation. The oven must also be high enough for all the users to reach inside. Together with this, the height of the hobs and the height of the oven must be found so that there is sufficient space inside the oven for food containers etc.

Another example is the depth of the sink which should be low enough for the wheelchair users to reach and high enough for the functionality of the sink, namely to contain water and items washed. The width of the sink must be big enough to put pots and pans and small enough for the users to reach the tap. The tap has to be in a position where all the users can reach it. The work surface and the shelves must be wide enough to contain items and the work surface must have enough room to prepare food etc. At the same time, the shelves and the work surface must not be too wide as to prevent some users from reaching the far edge.

It is the task of the optimisation to consider all the factors and find the best possible solution to all of them to increase the user accommodation. They were specified to the optimisation process by way of user centred objective functions, objective functions with regard to the physical aspects of the objects and functions that specify constraints as specified in chapter 4. If and when two or more of these objective functions or constraints conflict, the constraint modeller will find the solution considering the weighting factors given for them and giving priority to the rules with larger weighting factors.

As mentioned before, the SHIELDS optimisation capability stems from utilising the capability of SWORDS software. SHIELDS invokes SWORDS through Visual Basic code and then running macros. There is a bank of macros for SWORDS within SHIELDS to cater for various scenarios. These include the number of objects in an object group and the number of variables in objective functions.

For the kitchen workplace the largest group consists of 7 objects and there are 2 independent objects. All the objects in the dependent group are related to one another.

The maximum number of variables in any of the objects is 3. The user of SHIELDS can add any number of constraints to these macros. Here again equal priority was given to the constraints of the users and the constraints of the objects.

Initial values for variables were selected by studying the workplace and object positions. These initial values are important to guide the constraint modeller over local minima and to find a true optimal solution. In other words, if initial values were not specified, the constraint modeller may find a solution at a local minimum that would not satisfy all the given UOFs. This is especially important when the objective functions are as large as the given UOFs, which can be sensitive to small changes of the variables.

The whole optimisation model assembled using the above data is as follows.

Minimise all the following UOFs

If *i* is the number of subjects and *j* is the number of objects in the workplace, UOFs for reach and fit for the objects in the kitchen

$$f(r) = a_{ij} + b_{ij}x_{ij} + c_{ij}y_j + d_{ij}z_j + e_{ij}x_j^2 y_j + f_{ij}x_j y_j^2 + g_{ij}x_j^2 z_j + h_{ij}x_j z_j^2 + j_{ij}x_j y_j + i_{ij}x_j z_j + k_{ij}y_j z_j + l_{ij}x_j y_j z_j + m_{ij}x_j^2 y_j z_j + n_{ij}x_j y_j z_j^2 + p_{ij}x_j^2 y_j^2 z_j^2$$

where i = 1 to 10 and j = 1 to 9

UOFs for vision for the objects in the kitchen

$$f(v) = a_{ij} + b_{ij}x_j + c_{ij}y_j + d_{ij}z_j + e_{ij}x_j^2 y_j + f_{ij}x_j y_j^2 + g_{ij}x_j^2 z_j + h_{ij}x_j z_j^2 + j_{ij}x_j y_j + i_{ij}x_j z_j + k_{ij}y_j z_j + l_{ij}x_j y_j z_j + m_{ij}x_j^2 y_j z_j + n_{ij}x_j y_j z_j^2 + p_{ij}x_j^2 y_j^2 z_j^2$$

where i = 1 to 10 and j = 1 to 9

Each of these 180 UOFs were generated within SHIELDS and added to the macro that uses this optimisation model.

Optimisation was carried out to minimise each of these objective functions

Subject to $y_8 > y_5$ (a)

$y_8 > y_6$ (b)

$(z_5 - z_6) \geq a$ (c)

$0 < y_5 < y_8$ (d)

$0 < y_6 < y_8$ (e)

$z_6 - (z_7 + b) > c$ (f)

$(z_3 + h_1) = z_7 = (z_4 + d_1)$ (g)

$(z_1 + h_2) < (z_3 + h_1)$ (h)

$y_2 < y_4$ (i)

$(z_2 - z_4) = d_1$ (j)

$x_4 \leq x_2 \leq (x_4 + l_1)$ (k)

If $x_2 = x_4$ then $w_2 < (y_2 - y_4) < w_1$ (l)

If $x_2 = (x_4 + l_1)$ then $w_2 < (y_2 - y_4) < w_1$ (m)

Else if $x_4 < x_2 < (x_4 - l_1)$ then $w_2 < (y_2 - y_4) = w_1$ (n)

$(x_2 - x_4) > l_2$ (o)

$$3600 \leq \{(y_3 - ½ * w_3) - y_4\} + \{(x_9 + ½ * l_4) - (x_4 + ½ * l_2)\} + (\{(y_3 - ½ * w_3) - y_4\}^2 + \{(x_9 + ½ * l_4) - (x_4 + ½ * l_2)\}^2)^{½} \leq 6600 \quad (p)$$

And $v_{k\min} \leq v_k \leq v_{k\max}$ where v represents the variable and $k = 1$ to 9 (q)

Variables for this optimisation model are x_1, y_1, z_1, x_2, y_2, z_2, x_3, y_3, z_3, x_4, y_4, z_4, x_4, y_4, z_4, x_5, y_5, z_5, x_6, y_6, z_6, x_6, y_6, z_6, x_7, y_7, z_7, x_8, y_8, z_8, x_9, y_9, z_9, w_1, and h_1.

Of these variables x_1, x_3, x_5, x_6, x_7, x_8, y_9 were fixed for the optimisation and the others were freed to vary in order to minimise UOFs.

7.5 Results

When all the constraints described in the section 7.4.4 were specified to the constraint modeller, it could not find a satisfactory solution to the problem. This means that when all the constraints were considered the solution obtained was not within some constraints and had not minimised most of the UOFs. To overcome this over constrained problem, constraints that can be relaxed had to be found. By analysing the constraints list it was decided that the constraints that would least affect the functionality of the workplace are the two constraints specified by the constraint function (g) for the aesthetic reasons. Therefore these constraints were relaxed and the rest was optimised again.

The Table 7.4 shows the results obtained from the optimisation for the objects. From this it is clearly shown that the optimisation process has found the values that define the best solution for the design problem. The optimal values that have not changed at all from the initial values are for those variables that were fixed. For those objects that accommodated all the users, the optimal values have only been changed a little.

Table 7.4 - Results of the Optimisation

	x		y		z	
	Initial value	Optimal value	Initial value	Optimal value	Initial value	Optimal value
Oven	440	440	-1690	-1690	600	760.795
Cooker	0	0	-1950	-1950	1080	1120.8
Tap	808	807.344	-79	-261.62	1080	990.647
Sink	620	414.1	-440	-426.72	981	890.647
Shelf 1	40	40	-1120	-1039.97	1800	1458.87
Shelf 2	40	40	-1120	-1143.97	1600	1258.87
Work surface	0	0	-1420	-1409.51	1040	978.756
Clock	40	40	-2185	-2184.47	1764	1760.684
Fridge	1400	1404.81	-520	-520	200	200.24

Thus the optimisation has produced a set of new positions for all the objects specified in the group. The workplace modified according the obtained results is shown in the Figure 7.10. It shows how the positions have changed after the optimisation. Figure 7.11 shows the objects in their earlier positions before optimisation, for comparison. The basic layout of the workplace was retained by specifying ranges of values for the variables.

Figure 7.10 - New positions of the objects in the kitchen

Figure 7.11 – Positions of objects before optimisation

The optimisation process has found new values for both y and z co-ordinates of the work surface and shelves. It hasn't changed the positions of the fridge or the clock. It has found new z co-ordinates for the hobs and the oven and has retained their y co-ordinate with respect to each other in order to retain their positions in the cooker.

The most interesting result obtained was the position of the tap. Instead of its original position behind the sink, the constraint modeller has found a new position for the tap at the side of the sink, which is within the given constraints and can be accessed by all the users. The users can access all the other objects in their new positions except the upper shelf. The wheelchair users cannot access the upper shelf. Relaxing some constraints for the variables of the shelves could have rectified this but it would have changed the basic layout of the workplace. The total length of the three sides of the working triangle was calculated from the modified model of the kitchen. It was found to be 3823 mm, which is well within the specified range of between 3600 mm and 6600 mm.

7.6 Validation and Analysis

As with the earlier case study, the validation process was carried out by analysing the workplace modified according to the values found by the optimisation process using HADRIAN. Each of the tasks specified in section 7.4.3 was tested with the new model. The users selected to test the model are the same as the users of the earlier analysis. A summary of the results is given in Table 7.5.

Table 7.5 - User accommodation for the modified kitchen workplace

Task element	subjects (success = 1, failure = 0)										User accommodation	Importance to the overall task
	1	2	3	4	5	6	7	8	9	10		
Move in front of fridge	1	1	1	1	1	1	1	1	1	1	100%	necessary
Turn towards fridge	1	1	1	1	1	1	1	1	1	1	100%	necessary
View fridge door	1	1	1	1	1	1	1	1	1	1	100%	necessary
Reach fridge door	1	1	1	1	1	1	1	1	1	1	100%	necessary
View food element	1	1	1	1	1	1	1	1	1	1	100%	necessary
Reach food element	1	1	1	1	1	1	1	1	1	1	100%	necessary
Move in front of sink	1	1	1	1	1	1	1	1	1	1	100%	necessary
Turn towards sink	1	1	1	1	1	1	1	1	1	1	100%	necessary
View bottom of sink	1	1	1	1	1	1	1	1	1	1	100%	necessary
Reach bottom of sink	1	1	1	1	1	1	1	1	1	1	100%	necessary
View tap	1	1	1	1	1	1	1	1	1	1	100%	necessary
Reach tap	1	1	1	1	1	1	1	1	1	1	100%	necessary
Turn towards clock	1	1	1	1	1	1	1	1	1	1	100%	not a must
View clock	1	1	1	1	1	1	1	1	1	1	100%	not a must
Move closer to shelves	1	1	1	1	1	1	1	1	1	1	100%	necessary
Turn towards shelves	1	1	1	1	1	1	1	1	1	1	100%	necessary
View shelf 1	1	1	1	1	1	1	1	1	1	1	100%	necessary
View object on shelf 1	1	1	1	1	0	0	1	1	1	1	80%	necessary
Reach object on shelf 1	1	1	1	1	1	1	1	1	1	1	100%	necessary
View shelf 2	1	1	1	1	1	1	1	1	1	1	100%	necessary
View object on shelf 2	1	1	1	1	1	1	1	1	1	1	100%	necessary
Reach object on shelf 2	1	1	1	1	1	1	1	1	1	1	100%	necessary
Move to work surface	1	1	1	1	1	1	1	1	1	1	100%	necessary
Turn to work surface	1	1	1	1	1	1	1	1	1	1	100%	necessary
View work surface	1	1	1	1	1	1	1	1	1	1	100%	necessary
Reach work surface	1	1	1	1	1	1	1	1	1	1	100%	necessary
Turn towards clock	1	1	1	1	1	1	1	1	1	1	100%	not a must
View clock	1	1	1	1	1	1	1	1	1	1	100%	not a must
Move to cooker	1	1	1	1	1	1	1	1	1	1	100%	necessary
Turn towards cooker	1	1	1	1	1	1	1	1	1	1	100%	necessary
View back hob/pan 2	1	1	1	1	1	1	1	1	1	1	100%	necessary
Reach pan 2	1	1	1	1	1	1	1	1	1	1	100%	necessary
Turn towards clock	1	1	1	1	1	1	1	1	1	1	100%	not a must
View clock	1	1	1	1	1	1	1	1	1	1	100%	not a must
Move to oven	1	1	1	1	1	1	1	1	1	1	100%	necessary
Turn towards oven	1	1	1	1	1	1	1	1	1	1	100%	necessary
View tray	1	1	1	1	1	1	1	1	1	1	100%	necessary
Reach tray	1	1	1	1	1	1	1	1	1	1	100%	necessary
Turn towards clock	1	1	1	1	1	1	1	1	1	1	100%	not a must
View clock	1	1	1	1	1	1	1	1	1	1	100%	not a must

HADRIAN results files that detail these results are given in appendix 2. The user accommodation for the overall task obtained from this table is 80%. It also shows the individual users performance with respect to the task elements. These results as compared with the results shown in the Table 7.1 clearly show the increase in user accommodation in all the tasks specified. The only task element that has less than 100% user accommodation is the task 'reaching the shelf 1'. Even in this, there is an increase in the user accommodation compared with the earlier model. The user accommodation in reaching shelf 1 is less than 100% was because two users are unable to reach the upper shelf as mentioned in the results. These two users however can use the lower shelf.

At this point the designer has to decide whether to find entirely new positions for the shelves in order to get 100% user accommodation for the upper shelf or to retain the current position because they can reach at least one shelf. This can be achieved in the optimisation model by relaxing the constraints that bound the position of the shelf1 if necessary. It was not done in this case study in order to retain the position of the shelf with respect to other objects.

The new position of the tap shows that it is possible to get an entirely different position for an object that can be used by all the users within the given constraints by specifying the constraints accordingly. This can be used in situations to break away from traditional positions that sometimes affect the creativity of designers.

7.7 Conclusions

This case study contains 7 dependent objects and two independent objects. The positions of the dependent objects affect the positions of each other, which caused all of them to be considered together for the optimisation. The results obtained from the optimisation show that the new layout of the kitchen is better than the earlier one with regard to the user accommodation. The objective of Inclusive Design, that is to include all the users in the design, has been accomplished in 6 out of 7 tasks. This shows the use of the new software SHIELDS.

The three hypotheses made in the first chapter were confirmed true by the results of this case study. The first hypothesis that states 'If a user is unable to use a product or workplace because for example, it is out of reach, changing the parameters of that product or workplace and evaluating it with a computer model of the user to obtain a value for this failure, for example the out of reach distance, for each of these positions, will generate a path for this inability and that path can be mapped into a mathematical expression' is confirmed by using the user centred objective functions in the case study.

These objective functions, which were derived by fitting functions to the 'out of reach' distances, were made equal to zero in the optimisation process for the new values of the variables. This means that for these new values, i.e. the new positions of the objects, the users can reach the position, if the 'inability' has been correctly mapped into the function. From the validation tests, this has been found to be true hence proving the first hypothesis.

The second hypothesis states that 'Most of the factors required for the optimisation of physical aspects of a design concerning the users and the product or workplaces can be expressed as mathematical functions enabling them to be used in an optimisation process with any other constraints that affect the product'. The physical aspects of the users were mathematically expressed in the above mentioned user centred objective functions. The factors regarding the workplace were expressed to the system in the form of constraint functions, which had been used in the optimisation process. The results of the case study shows that all these have been adequately expressed in mathematical form which confirm the second hypothesis.

The third hypothesis, 'The Inclusive Design Synthesis problem can be structured in such a way that it can be implemented in a software system to ensure it being evaluated and practically formulated in an optimisation process and then being able to solve it' has been sufficiently proven by the successful results of this case study.

The case study has proven that SHIELDS is capable of handling several interdependent objects that have one, two or three degrees of freedom each. SHIELDS, while considering these objects separately on one hand has regarded them all together on the other hand with the constraints that relate them. The results obtained have also shown that SHIELDS is capable of finding the optimum value for a given position that maximises the user accommodation. This was accomplished by incorporating physical characteristics of the users of the product in the optimisation process.

By way of obtaining user centred objective functions SHIELDS has incorporated the above users' anthropometrics, joint constraints, capabilities as well as coping strategies in the optimisation process to find better solutions to workplace design. The case study results have also shown that SHIELDS is capable of evaluating and optimising reach and fit as well as vision although the SHIELDS operator has to play a role in evaluating vision. This could be rectified and the vision evaluation taken out of the operators eyes with further development of SAMMIE software vision capability and interference detection.

7.8 Summary

In this chapter a case study was presented that tested the capabilities of SHIELDS. The results obtained from the case study and the validation performed in HADRIAN has shown that the method developed to maximise the use accommodation in a product or workplace is valid and works. It has also proven the hypotheses made in chapter 1. Interdependency between the objects analysed and SHIELDS ability to optimise objects, which have several degrees of freedom, as well as its ability to evaluate reach, fit and vision were tested. More importantly how well SHIELDS accommodates the users in the optimisation process was tested. The results shows that SHIELDS has the capability to accommodate all the necessary characteristics of the users to accommodate them in the optimisation process to optimise the physical characteristics of a product or a workplace considering reach, fit and vision.

The next chapter summarises and concludes the thesis and also identifies future work that could be carried out.

Chapter 8

Discussion and Conclusion

8.1 Chapter Overview

A brief discussion of the research is presented in this chapter. It also summarises the research, and its findings and draws out the conclusions. Then it goes on to affirm the contribution made to the general knowledge by this research. Further research opportunities instigating from this work are also suggested in brief.

8.2 Discussion

A methodology that has been developed to implement the concept of Inclusive Design is presented in this thesis. As shown in earlier chapters and especially in chapter 4, this methodology integrates the characteristics of the users of products or workplaces with the aspects of that product or workplace, in a design optimisation process. This optimisation process has been carried out to optimise the physical layout of objects in a product or workplace. It must be noted here that only the physical aspects of users and products have been considered. These physical characteristics of the users such as anthropometrics, capabilities and joint constraints have been converted to mathematical formulae with the use of ergonomic analysis and mathematical methods. These formulae were then modelled as constraints in a constraint-modelling environment together with the constraints of the product to find better solutions. Application of constraint modelling techniques to model the physical constraints of the individual users in a design problem has been carried out successfully. The whole Inclusive Design synthesis problem that aims to find better layouts of objects in a product or workplace has been modelled using constraints in this method. This problem is then solved within a constraint modeller.

The implementation of Inclusive Design requires a great deal of understanding of the capabilities of the users and their needs as well as the functionality of the products and workplaces. This research has proposed that to achieve inclusivity in designs, the characteristics of the users must be considered during the design stage. There are various methods of employing the data of users in the design of products. With regard to these user data, this research utilises the ideas developed by the 'Design for All' project group in Loughborough University with respect to the innovative use of individual data of users when designing for the whole population. The traditional method of employing user data was to use anthropometric data collected for a certain population. If data for a certain percentile person is needed it was extracted from this data. From these statistically presented anthropometric data for a population it is impossible to recreate the data of the original persons who have been measured. Therefore the designers have virtually no knowledge of the people behind these numbers.

Having an understanding of each and every user puts the designer in a better position to design products and workplaces for them. Understandably, this is a monumental task, especially when various disabilities of the population are considered. But ultimately it will give the results in the form of inclusively designed, very desirable products and workplaces. However, to implement any design method using this data of individuals, all the aspects of the users, which create a huge multivariate database, must be considered at the design stage of a product or a workplace. The methodology developed is capable of handling most of these data.

A computer tool has been developed to implement this methodology. This software, called SHIELDS, is able to analyse tasks using a model of the product or workplace. For this analysis it uses a database of individuals that is contained within the system. With the designer's input of constraints regarding the product, the system is able to suggest design parameters that maximise the user accommodation. The system also outputs information regarding individual users who are able/unable to use the product with its new parameters. However this methodology has not taken into account the users with visual impairment and who have limitation with regard to the strength etc. It is acknowledged that for a truly Inclusive Design these aspects must also be considered fully.

Under-constraining a design problem has not been a problem for the software because the constraint modeller used, SWORDS, finds a feasible solution within the given constraints. Over constrained problems were solved by concentrating on the constraints that have larger weighting factors. These factors were assigned by the designer who can also interactively apply more constraints or relax constraints. These weighting factors can be used to specify to the system, which constraints must be satisfied or which can be relaxed.

This methodology and the software tool has been tested and validated by performing two case studies. These were discussed in detail in chapters 6 and 7. These two case studies have shown that the software works satisfactorily. The intended role of this software system is for the designer to provide the model of the workplace, the tasks to be performed and the constraints. Then the evaluation of the tasks is done within the system, which also provides the database of the users. Also the conversion of user constraints into a mathematical function is done within the system without resolving the constraints, allowing the designer to specify the tasks and the constraints ensures that the designer is in control of the design process. Then the designer lets the system find a better solution for the design problem.

This software helps designers to model and evaluate products and workplaces without actual users being involved. Actual user trials are costly and time consuming and with regard to the disabled and the elderly people, sometimes impossible. In those situations the software discussed in this thesis can provide designers with a potentially acceptable solution instead of having to employ numerous user trials with various designs. However it is not the intension of this research to replace user trials, rather this methodology will simplify the user trials and provide a solution where user trials are impossible due to various reasons.

The extensive review of literature conducted on the implementation of Inclusive Design has shown that,

- Inclusive Design concepts in the US, UK and Europe are establishing well despite it being a relatively new concept and countries like Australia and Japan are also studying these ideas. Increasingly these ideas are being turned into inclusively designed products using a variety of methods. These methods mainly focus on using population data of disabled and elderly people in traditional designing processes. By and large there is no guarantee that all the people in the user population are able to utilise these products when they are rolled out into the markets. However, there is a huge amount of interest in the research field in this area (Mueller, 2000, Benktzon, 1993, Keates et al, 2002, Coy et al, 2001).
- It has been seen that inclusively designed products offer greater benefits socially and economically to the society at large. It may also bring economic benefits to designers and manufacturers as well. Legal requirements are appearing that may force the use of these products on the society (Steinfeld 1994).
- Research is being conducted to gather information and analyse the user capabilities, which is central to the Inclusive Design approach. Also design criteria for Inclusive Design products and evaluation methods for the designed products are being developed by researchers (Case et al, 2000, Porter et al, 2002, Clarkson et al, 2000, Keates and Clarkson, 2001).
- However a number of drawbacks in this previous research have been identified and these mainly include the lack of public awareness of the concept and more

importantly, the lack of tools that designers can use in order to efficiently design inclusively designed products or workplaces. There are less than a handful of design tools that have been developed exclusively to implement Inclusive Design. These tools are still mainly in research and not commercially available. Of these tools the I~Design tool and the Inclusive Design cube involve helping the designer in the process of educating them on the Inclusive Design principles and the application of its strategies as well as the estimation of the population coverage (Lebbon, 2003, Keates et al, 2002). The other inclusive design tool HADRIAN provides the designer with the capability of evaluating a CAD model of a product or a workplace against individual users (Marshall et al, 2002). These tools however do not present the designer with much help with regard to the details of a design such as defining precise layouts or dimensions of a product or a workplace that maximises the user accommodation.

A question arising from the use of individual data is that can a single design be found to include all and also is it possible to find data regarding each and every individual? To include all individuals some aspects of the products must be relaxed, for example aesthetics or new solutions for these aesthetic problems must be found that satisfy the functionality and user inclusion of the design.

The methodology presented in this thesis has addressed the designers' problem of not having an convenient methodology and a tool to aid in the process of achieving Inclusive Design by developing the methodology discussed and the software tool SHIELDS.

8.3 Conclusions

- A new methodology has been developed by this research in order to increase the user accommodation of a product design by considering the characteristics of individual users including those of, elderly, disabled and able-bodied.
- A prototype software tool has been developed to implement the above-mentioned methodology and thus be able to predict values for design variables that would increase the user accommodation.
- The utilisation of this software SHIELDS in performing the two case studies has shown its ability to suggest better solutions to Inclusive Design problems by incorporating the physical aspects of the users of products and also physical constraints of the product. By manipulating the constraints appropriately the designer may able to find acceptable but unexpected solutions that solve the

design problem without going into complicated rearrangements or redesigns. This can be seen in the kitchen design in chapter 7.

- The methodology developed, when used within SHIELDS provides a faster and more convenient method of finding better solutions to design problems that require finding new layouts for objects in a products or a workplace with respect to the users who use it. Traditional methods would involve evaluating various positions of objects with each user performing each and every task element to achieve inclusively designed products. Even with a computer human modelling system like SAMMIE and task analysis tools such as HADRIAN, this could take a large amount of time and manpower. The new methodology developed can solve the problem within relatively short time depending on the problem.

- In developing this methodology, the constraint modelling technique has been used in a new field of Inclusive Design to model the physical characteristics of the users of products.

- Most types of constraints e.g. engineering constraints, geometric constraints etc. can be specified into the SHIELDS system, as long as they can be expressed as algebraic functions. Also SHIELDS can accommodate a large number of these constraint functions.

- An innovative approach to design that has been initiated by the researchers at Loughborough University has been utilised in this research in using data of individuals as opposed to population data. This has enabled the designer to visualise each and every user at the beginning of the design process, which helps in achieving inclusivity in product design.

- Each task the individual users needs to perform when interacting with the products or workplaces is evaluated ergonomically. These tasks are broken down into task elements and the user's ability to perform each task element is analysed by the system to find a solution that overcomes any inability.

- The sub problems raised in chapter 1 section 1.9 have been answered sufficiently in chapter 6 and 7 and the hypotheses made were tested in them as well.

  Sub-problem 1 raised the issue of whether a user's capability and constraints could be structured in a mathematical form to be used in an optimisation problem. This problem has been answered with the hypothesis made which stated that the users' physical inability to use a product could be mapped into a mathematical equation by evaluating the model of the workplace or product with user models. The two case studies have shown that it is possible to map these physical inabilities in mathematical form, which were then used in optimisation problems.

Sub-problem 2 questions whether the Inclusive Design Synthesis problem could be constructed as an optimisation problem which takes into account users' physical factors as well as the constraints of the products or workplace to find better solutions by using optimisation methods. This problem was solved with the use of the hypothesis that states that all the factors that are required for the optimisation of physical aspects of a design concerning the users and the product or workplaces can be expressed as mathematical functions together with other constraints that affect the product, which can be used in an optimisation model. In the two case studies, factors regarding the users were expressed in mathematical terms by the use of the UOFs and the constraints that define the designs were also expressed in mathematical terms. These were then used in an optimisation model, which the constraint modeller has solved using optimisation methods to find solutions proving the hypothesis.

Sub-problem 3 expresses the issue whether a fully functional software system could be created from the existing software to model, evaluate and solve the Inclusive Design Synthesis problem. This problem was solved with use of the hypothesis, which states that the Inclusive Design Synthesis problem can be structured in such a way that it can be implemented in a software system ensuring it being evaluated and practically formulated in a soluble optimisation process. This hypothesis was tested by the creation of SHIELDS and its successful use in the two case studies the results of which had been validated by testing the design suggested by SHIELDS in HADRIAN.

- The work performed in this research has shown that it is possible to incorporate the physical aspects of the users in the optimum design process.
- The literature has shown that there are many different viewpoints of researchers about the Inclusive Design concepts. Although the Universal Design Centre in US has initiated the principles of 'universal design', many new ideas are immerging from UK and the Europe.
- The literature has also shown that the Inclusive Design concepts are now becoming firmly established although there is still a long way to go before it becomes a part of the society.

8.4 Contribution

The contribution that has been made by this research is the development of the methodology that can increase the user accommodation of a product with the intention of achieving inclusivity in designs. This has been done by including the physical aspects of the individual users in the design optimisation process together with the constraints of the product or workplace. This methodology that uses constraint modelling and ergonomics evaluation in an Inclusive Design environment, is able to suggest values for design variables that accommodate the maximum percentage of users in a particular design. In this process, aspects of each user are being tested individually with regard to the tasks they have to perform when using the product or workplace.

8.5 Future Research

- Inclusive Design is designing products and workplaces that can be used by all the people in the society regardless of their age or ability and without stigmatising anybody. This includes people with limited strength, visual impairment, and reading disability etc. as well as the people with physical disability. This research has considered only the physical disabilities of people. Avenues of accommodating the users with other types of disabilities in the design process are worth investigating in a research project.

  The design of products that can be used by people with all types of abilities and disabilities is a huge task. The first step in this should be the proper understanding of the type of disability and how the products can be developed that could be used by people with these disabilities. For example the method used in this research has relocated objects for the users to reach and see them. When considering people with limited strength, the products can be made which require less force to use. To find these firstly extensive surveys of user populations could be carried out. Methods for developing techniques to accommodate users with types of disabilities other than physical would arise from these surveys.

- This research has considered only the re-layout of objects within the products and workplaces being designed. However the methodology developed can be expanded – additional objective functions can be set in the optimisation process in chapter 4 – to incorporate other aspects of the design such as resizing or functionality aspects. For example if a product's dimensions can be changed, mathematical functions regarding this such as material usage or structural stability can be added to the optimisation model. Further research into this area could enhance the design of products with regard to the user accommodation and Inclusive Design concepts by allowing other aspects of the design in the optimisation.

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Appendix 1

HADRIAN generated results file for the ATM task analysis.

(These results are arranged in column form to save space)

HADRIAN analysis results before optimisation

```
! HADRIAN generated results file.
!
! -------------------------------------
! TASK RESULTS
Task: ATM Analysis
Model:

Subject11
-------------------- ----
Task Element:      1
Command:           LOOK
Target Name:       Screen
Target Location:   -4.00    698.00    1575.00
Result:            SUCCESS
Final posture code: 110000000000
-------------------- ----
Task Element:      2
Command:           LOOK
Target Name:       Slot
Target Location:   140.00   698.00    1512.00
Result:            SUCCESS
Final posture code: 110000000000
-------------------- ----
Task Element:      3
Command:           REACH
Target Name:       Slot
Target Location:   140.00   698.00    1512.00
Result:            FAILURE
Final posture code: 112311111111
-------------------- ----
Task Element:      4
Command:           LOOK
Target Name:       Dispenser
Target Location:   37.00    698.00    1285.00
Result:            SUCCESS
Final posture code: 120000000000
-------------------- ----
Task Element:      5
Command:           REACH
Target Name:       Dispenser
Target Location:   37.00    698.00    1285.00
Result:            SUCCESS
Final posture code: 122111221111
-------------------- ----
Task Element:      6
Command:           LOOK
Target Name:       Keys
Target Location:   41.00    592.00    1238.00
Result:            SUCCESS
Final posture code: 120000000000
-------------------- ----
Task Element:      7
Command:           REACH
Target Name:       Keys
Target Location:   41.00    592.00    1238.00
Result:            SUCCESS
Final posture code: 122111111111

Subject12
-------------------- ----
Task Element:      1
Command:           LOOK
Target Name:       Screen
Target Location:   -4.00    698.00    1575.00
Result:            SUCCESS
Final posture code: 110000000000
-------------------- ----
Task Element:      2
Command:           LOOK
Target Name:       Slot
Target Location:   140.00   698.00    1512.00
Result:            SUCCESS
Final posture code: 110000000000
-------------------- ----
Task Element:      3
Command:           REACH
Target Name:       Slot
Target Location:   140.00   698.00    1512.00
Result:            FAILURE
Final posture code: 112311111111
-------------------- ----
Task Element:      4
Command:           LOOK
Target Name:       Dispenser
Target Location:   37.00    698.00    1285.00
Result:            SUCCESS
Final posture code: 120000000000
-------------------- ----
Task Element:      5
Command:           REACH
Target Name:       Dispenser
Target Location:   37.00    698.00    1285.00
Result:            SUCCESS
Final posture code: 122111221111
-------------------- ----
Task Element:      6
Command:           LOOK
Target Name:       Keys
Target Location:   41.00    592.00    1238.00
Result:            SUCCESS
Final posture code: 120000000000
-------------------- ----
Task Element:      7
Command:           REACH
Target Name:       Keys
Target Location:   41.00    592.00    1238.00
Result:            SUCCESS
Final posture code: 122111111111

Subject27
-------------------- ----
Task Element:      1
Command:           LOOK
Target Name:       Screen
Target Location:   -4.00    698.00    1575.00
Result:            SUCCESS
Final posture code: 110000000000
-------------------- ----
Task Element:      2
Command:           LOOK
Target Name:       Slot
Target Location:   140.00   698.00    1512.00
```

Result: SUCCESS
Final posture code: 110000000000

-------------------- ----
Task Element: 3
Command: REACH
Target Name: Slot
Target Location: 140.00 698.00 1512.00
Result: SUCCESS
Final posture code: 112311221111
-------------------- ----
Task Element: 4
Command: LOOK
Target Name: Dispenser
Target Location: 37.00 698.00 1285.00
Result: SUCCESS
Final posture code: 120000000000
-------------------- ----
Task Element: 5
Command: REACH
Target Name: Dispenser
Target Location: 37.00 698.00 1285.00
Result: SUCCESS
Final posture code: 122111221111
-------------------- ----
Task Element: 6
Command: LOOK
Target Name: Keys
Target Location: 41.00 592.00 1238.00
Result: SUCCESS
Final posture code: 120000000000
-------------------- ----
Task Element: 7
Command: REACH
Target Name: Keys
Target Location: 41.00 592.00 1238.00
Result: SUCCESS
Final posture code: 122111111111

Subject28
-------------------- ----
Task Element: 1
Command: LOOK
Target Name: Screen
Target Location: -4.00 698.00 1575.00
Result: SUCCESS
Final posture code: 110000000000
-------------------- ----
Task Element: 2
Command: LOOK
Target Name: Slot
Target Location: 140.00 698.00 1512.00
Result: SUCCESS
Final posture code: 110000000000
-------------------- ----
Task Element: 3
Command: REACH
Target Name: Slot
Target Location: 140.00 698.00 1512.00
Result: FAILURE
Final posture code: 112311111111
-------------------- ----
Task Element: 4
Command: LOOK
Target Name: Dispenser
Target Location: 37.00 698.00 1285.00
Result: SUCCESS
Final posture code: 120000000000
-------------------- ----
Task Element: 5
Command: REACH
Target Name: Dispenser
Target Location: 37.00 698.00 1285.00
Result: SUCCESS
Final posture code: 122111221111

-------------------- ----
Task Element: 6
Command: LOOK
Target Name: Keys
Target Location: 41.00 592.00 1238.00
Result: SUCCESS
Final posture code: 120000000000
-------------------- ----
Task Element: 7
Command: REACH
Target Name: Keys
Target Location: 41.00 592.00 1238.00
Result: SUCCESS
Final posture code: 122111111111

Subject40
-------------------- ----
Task Element: 1
Command: LOOK
Target Name: Screen
Target Location: -4.00 698.00 1575.00
Result: SUCCESS
Final posture code: 110000000000
-------------------- ----
Task Element: 2
Command: LOOK
Target Name: Slot
Target Location: 140.00 698.00 1512.00
Result: SUCCESS
Final posture code: 110000000000
-------------------- ----
Task Element: 3
Command: REACH
Target Name: Slot
Target Location: 140.00 698.00 1512.00
Result: FAILURE
Final posture code: 112571112111
-------------------- ----
Task Element: 4
Command: LOOK
Target Name: Dispenser
Target Location: 37.00 698.00 1285.00
Result: SUCCESS
Final posture code: 010000000000
-------------------- ----
Task Element: 5
Command: REACH
Target Name: Dispenser
Target Location: 37.00 698.00 1285.00
Result: FAILURE
Final posture code: 012571112111
-------------------- ----
Task Element: 6
Command: LOOK
Target Name: Keys
Target Location: 41.00 592.00 1238.00
Result: SUCCESS
Final posture code: 110000000000
-------------------- ----
Task Element: 7
Command: REACH
Target Name: Keys
Target Location: 41.00 592.00 1238.00
Result: SUCCESS
Final posture code: 112171112111

Subject41
-------------------- ----
Task Element: 1
Command: LOOK
Target Name: Screen
Target Location: -4.00 698.00 1575.00
Result: SUCCESS
Final posture code: 110000000000
-------------------- ----

Task Element: 2
Command: LOOK
Target Name: Slot
Target Location: 140.00 698.00 1512.00
Result: SUCCESS
Final posture code: 110000000000
-------------------- ----

Task Element: 3
Command: REACH
Target Name: Slot
Target Location: 140.00 698.00 1512.00
Result: FAILURE
Final posture code: 112571112111
-------------------- ----
Task Element: 4
Command: LOOK
Target Name: Dispenser
Target Location: 37.00 698.00 1285.00
Result: SUCCESS
Final posture code: 010000000000
-------------------- ----
Task Element: 5
Command: REACH
Target Name: Dispenser
Target Location: 37.00 698.00 1285.00
Result: SUCCESS
Final posture code: 012571112111
-------------------- ----
Task Element: 6
Command: LOOK
Target Name: Keys
Target Location: 41.00 592.00 1238.00
Result: SUCCESS
Final posture code: 310000000000
-------------------- ----
Task Element: 7
Command: REACH
Target Name: Keys
Target Location: 41.00 592.00 1238.00
Result: SUCCESS
Final posture code: 312571112111

Subject47
-------------------- ----
Task Element: 1
Command: LOOK
Target Name: Screen
Target Location: -4.00 698.00 1575.00
Result: SUCCESS
Final posture code: 110000000000
-------------------- ----
Task Element: 2
Command: LOOK
Target Name: Slot
Target Location: 140.00 698.00 1512.00
Result: SUCCESS
Final posture code: 110000000000
-------------------- ----
Task Element: 3
Command: REACH
Target Name: Slot
Target Location: 140.00 698.00 1512.00
Result: SUCCESS
Final posture code: 112311221111
-------------------- ----
Task Element: 4
Command: LOOK
Target Name: Dispenser
Target Location: 37.00 698.00 1285.00
Result: SUCCESS
Final posture code: 120000000000
-------------------- ----
Task Element: 5
Command: REACH
Target Name: Dispenser
Target Location: 37.00 698.00 1285.00
Result: SUCCESS
Final posture code: 122111221111
-------------------- ----
Task Element: 6
Command: LOOK
Target Name: Keys
Target Location: 41.00 592.00 1238.00
Result: SUCCESS
Final posture code: 120000000000
-------------------- ----
Task Element: 7
Command: REACH
Target Name: Keys
Target Location: 41.00 592.00 1238.00
Result: SUCCESS
Final posture code: 122111111111

Subject54
-------------------- ----
Task Element: 1
Command: LOOK
Target Name: Screen
Target Location: -4.00 698.00 1575.00
Result: SUCCESS
Final posture code: 110000000000
-------------------- ----
Task Element: 2
Command: LOOK
Target Name: Slot
Target Location: 140.00 698.00 1512.00
Result: SUCCESS
Final posture code: 110000000000
-------------------- ----
Task Element: 3
Command: REACH
Target Name: Slot
Target Location: 140.00 698.00 1512.00
Result: SUCCESS
Final posture code: 112311221111
-------------------- ----
Task Element: 4
Command: LOOK
Target Name: Dispenser
Target Location: 37.00 698.00 1285.00
Result: SUCCESS
Final posture code: 120000000000
-------------------- ----
Task Element: 5
Command: REACH
Target Name: Dispenser
Target Location: 37.00 698.00 1285.00
Result: SUCCESS
Final posture code: 122111221111
-------------------- ----
Task Element: 6
Command: LOOK
Target Name: Keys
Target Location: 41.00 592.00 1238.00
Result: SUCCESS
Final posture code: 120000000000
-------------------- ----
Task Element: 7
Command: REACH
Target Name: Keys
Target Location: 41.00 592.00 1238.00
Result: SUCCESS
Final posture code: 122111111111

Subject97
-------------------- ----
Task Element: 1
Command: LOOK
Target Name: Screen

Target Location: 0.00 0.00 0.00
Result: SUCCESS
Final posture code: 110000000000
-------------------- ----
Task Element: 2
Command: LOOK
Target Name: Slot
Target Location: 140.00 698.00 1512.00
Result: SUCCESS
Final posture code: 110000000000
-------------------- ----
Task Element: 3
Command: REACH
Target Name: Slot
Target Location: 140.00 698.00 1512.00
Result: SUCCESS
Final posture code: 112311221111
-------------------- ----
Task Element: 4
Command: LOOK
Target Name: Dispenser
Target Location: 37.00 698.00 1285.00
Result: SUCCESS
Final posture code: 120000000000
-------------------- ----
Task Element: 5
Command: REACH
Target Name: Dispenser
Target Location: 37.00 698.00 1285.00
Result: SUCCESS
Final posture code: 122111221111
-------------------- ----
Task Element: 6
Command: LOOK
Target Name: Keys
Target Location: 41.00 592.00 1238.00
Result: SUCCESS
Final posture code: 120000000000
-------------------- ----
Task Element: 7
Command: REACH
Target Name: Keys
Target Location: 41.00 592.00 1238.00
Result: SUCCESS
Final posture code: 122111111111
Subject98
-------------------- ----
Task Element: 1
Command: LOOK
Target Name: Screen
Target Location: -4.00 698.00 1575.00
Result: SUCCESS
Final posture code: 110000000000
-------------------- ----
Task Element: 2
Command: LOOK
Target Name: Slot
Target Location: 140.00 698.00 1512.00
Result: SUCCESS
Final posture code: 110000000000
-------------------- ----
Task Element: 3
Command: REACH
Target Name: Slot
Target Location: 140.00 698.00 1512.00
Result: FAILURE
Final posture code: 112311111111
-------------------- ----
Task Element: 4
Command: LOOK
Target Name: Dispenser
Target Location: 37.00 698.00 1285.00
Result: SUCCESS
Final posture code: 110000000000
-------------------- ----
Task Element: 5
Command: REACH
Target Name: Dispenser
Target Location: 37.00 698.00 1285.00
Result: FAILURE
Final posture code: 112111111111
-------------------- ----
Task Element: 6
Command: LOOK
Target Name: Keys
Target Location: 41.00 592.00 1238.00
Result: SUCCESS
Final posture code: 110000000000
-------------------- ----
Task Element: 7
Command: REACH
Target Name: Keys
Target Location: 41.00 592.00 1238.00
Result: SUCCESS
Final posture code: 112111111111

HADRIAN analysis for validation after optimisation

! HADRIAN generated res12ults file.
!
! -------------------------------------
! TASK RESULTS
Task: ATM Analysis
Model:

Subject11
-------------------- ----
Task Element: 1
Command: LOOK
Target Name: Screen
Target Location: -4.00 696.52 1068.7
Result: SUCCESS
Final posture code: 110000000000
-------------------- ----
Task Element: 2
Command: LOOK
Target Name: Slot
Target Location: 140.00 696.52 1005.12
Result: SUCCESS
Final posture code: 110000000000
-------------------- ----
Task Element: 3
Command: REACH
Target Name: Slot
Target Location: 140.00 696.52 1005.12
Result: SUCCESS
Final posture code: 112311111111
-------------------- ----
Task Element: 4
Command: LOOK
Target Name: Dispenser
Target Location: 37.00 696.52 925.094
Result: SUCCESS
Final posture code: 120000000000
-------------------- ----
Task Element: 5
Command: REACH
Target Name: Dispenser
Target Location: 37.00 696.52 925.094
Result: SUCCESS

Final posture code: 122111221111
-------------------- ----
Task Element: 6
Command: LOOK
Target Name: Keys
Target Location: 41.00 592.00 732.2
Result: SUCCESS
Final posture code: 120000000000
-------------------- ----
Task Element: 7
Command: REACH
Target Name: Keys
Target Location: 41.00 592.00 732.2
Result: SUCCESS
Final posture code: 122111111111

Subject12
-------------------- ----
Task Element: 1
Command: LOOK
Target Name: Screen
Target Location: -4.00 696.52 1068.7
Result: SUCCESS
Final posture code: 110000000000
-------------------- ----
Task Element: 2
Command: LOOK
Target Name: Slot
Target Location: 140.00 696.52 1005.12
Result: SUCCESS
Final posture code: 110000000000
-------------------- ----
Task Element: 3
Command: REACH
Target Name: Slot
Target Location: 140.00 696.52 1005.12
Result: SUCCESS
Final posture code: 112311111111
-------------------- ----
Task Element: 4
Command: LOOK
Target Name: Dispenser
Target Location: 37.00 696.52 925.094
Result: SUCCESS
Final posture code: 120000000000
-------------------- ----
Task Element: 5
Command: REACH
Target Name: Dispenser
Target Location: 37.00 696.52 925.094
Result: SUCCESS
Final posture code: 122111221111
-------------------- ----
Task Element: 6
Command: LOOK
Target Name: Keys
Target Location: 41.00 592.00 732.2
Result: SUCCESS
Final posture code: 120000000000
-------------------- ----
Task Element: 7
Command: REACH
Target Name: Keys
Target Location: 41.00 592.00 732.2
Result: SUCCESS
Final posture code: 122111111111

Subject27
-------------------- ----
Task Element: 1
Command: LOOK
Target Name: Screen
Target Location: -4.00 696.52 1068.7
Result: SUCCESS
Final posture code: 110000000000
-------------------- ----
Task Element: 2
Command: LOOK
Target Name: Slot
Target Location: 140.00 696.52 1005.12
Result: SUCCESS
Final posture code: 110000000000

-------------------- ----
Task Element: 3
Command: REACH
Target Name: Slot
Target Location: 140.00 696.52 1005.12
Result: SUCCESS
Final posture code: 112311221111
-------------------- ----
Task Element: 4
Command: LOOK
Target Name: Dispenser
Target Location: 37.00 696.52 925.094
Result: SUCCESS
Final posture code: 120000000000
-------------------- ----
Task Element: 5
Command: REACH
Target Name: Dispenser
Target Location: 37.00 696.52 925.094
Result: SUCCESS
Final posture code: 122111221111
-------------------- ----
Task Element: 6
Command: LOOK
Target Name: Keys
Target Location: 41.00 592.00 732.2
Result: SUCCESS
Final posture code: 120000000000
-------------------- ----
Task Element: 7
Command: REACH
Target Name: Keys
Target Location: 41.00 592.00 732.2
Result: SUCCESS
Final posture code: 122111111111

Subject28
-------------------- ----
Task Element: 1
Command: LOOK
Target Name: Screen
Target Location: -4.00 696.52 1068.7
Result: SUCCESS
Final posture code: 110000000000
-------------------- ----
Task Element: 2
Command: LOOK
Target Name: Slot
Target Location: 140.00 696.52 1005.12
Result: SUCCESS
Final posture code: 110000000000
-------------------- ----
Task Element: 3
Command: REACH
Target Name: Slot
Target Location: 140.00 696.52 1005.12
Result: SUCCESS
Final posture code: 112311111111
-------------------- ----
Task Element: 4
Command: LOOK
Target Name: Dispenser
Target Location: 37.00 696.52 925.094
Result: SUCCESS
Final posture code: 120000000000
-------------------- ----
Task Element: 5

Command: REACH
Target Name: Dispenser
Target Location: 37.00 696.52 925.094
Result: SUCCESS
Final posture code: 122111221111
-------------------- ----
Task Element: 6
Command: LOOK
Target Name: Keys
Target Location: 41.00 592.00 732.2
Result: SUCCESS
Final posture code: 120000000000
-------------------- ----
Task Element: 7
Command: REACH
Target Name: Keys
Target Location: 41.00 592.00 732.2
Result: SUCCESS
Final posture code: 122111111111

Subject40
-------------------- ----
Task Element: 1
Command: LOOK
Target Name: Screen
Target Location: -4.00 696.52 1068.7
Result: SUCCESS
Final posture code: 110000000000
-------------------- ----
Task Element: 2
Command: LOOK
Target Name: Slot
Target Location: 140.00 696.52 1005.12
Result: SUCCESS
Final posture code: 110000000000
-------------------- ----
Task Element: 3
Command: REACH
Target Name: Slot
Target Location: 140.00 696.52 1005.12
Result: SUCCESS
Final posture code: 112571112111
-------------------- ----
Task Element: 4
Command: LOOK
Target Name: Dispenser
Target Location: 37.00 696.52 925.094
Result: SUCCESS
Final posture code: 010000000000
-------------------- ----
Task Element: 5
Command: REACH
Target Name: Dispenser
Target Location: 37.00 696.52 925.094
Result: SUCCESS
Final posture code: 012571112111
-------------------- ----
Task Element: 6
Command: LOOK
Target Name: Keys
Target Location: 41.00 592.00 732.2
Result: SUCCESS
Final posture code: 110000000000
-------------------- ----
Task Element: 7
Command: REACH
Target Name: Keys
Target Location: 41.00 592.00 732.2
Result: SUCCESS
Final posture code: 112171112111

Subject41
-------------------- ----
Task Element: 1
Command: LOOK
Target Name: Screen
Target Location: -4.00 696.52 1068.7
Result: SUCCESS
Final posture code: 110000000000
-------------------- ----
Task Element: 2
Command: LOOK
Target Name: Slot
Target Location: 140.00 696.52 1005.12
Result: SUCCESS
Final posture code: 110000000000
-------------------- ----

Task Element: 3
Command: REACH
Target Name: Slot
Target Location: 140.00 696.52 1005.12
Result: SUCCESS
Final posture code: 112571112111
-------------------- ----
Task Element: 4
Command: LOOK
Target Name: Dispenser
Target Location: 37.00 696.52 925.094
Result: SUCCESS
Final posture code: 010000000000
-------------------- ----
Task Element: 5
Command: REACH
Target Name: Dispenser
Target Location: 37.00 696.52 925.094
Result: SUCCESS
Final posture code: 012571112111
-------------------- ----
Task Element: 6
Command: LOOK
Target Name: Keys
Target Location: 41.00 592.00 732.2
Result: SUCCESS
Final posture code: 310000000000
-------------------- ----
Task Element: 7
Command: REACH
Target Name: Keys
Target Location: 41.00 592.00 732.2
Result: SUCCESS
Final posture code: 312571112111

Subject47
-------------------- ----
Task Element: 1
Command: LOOK
Target Name: Screen
Target Location: -4.00 696.52 1068.7
Result: SUCCESS
Final posture code: 110000000000
-------------------- ----
Task Element: 2
Command: LOOK
Target Name: Slot
Target Location: 140.00 696.52 1005.12
Result: SUCCESS
Final posture code: 110000000000
-------------------- ----
Task Element: 3
Command: REACH
Target Name: Slot
Target Location: 140.00 696.52 1005.12
Result: SUCCESS
Final posture code: 112311221111
-------------------- ----
Task Element: 4
Command: LOOK
Target Name: Dispenser
Target Location: 37.00 696.52 925.094

Result: SUCCESS
Final posture code: 120000000000
--------------------- ----
Task Element: 5
Command: REACH
Target Name: Dispenser
Target Location: 37.00 696.52 925.094
Result: SUCCESS
Final posture code: 122111221111
--------------------- ----
Task Element: 6
Command: LOOK
Target Name: Keys
Target Location: 41.00 592.00 732.2
Result: SUCCESS
Final posture code: 120000000000
--------------------- ----
Task Element: 7
Command: REACH
Target Name: Keys
Target Location: 41.00 592.00 732.2
Result: SUCCESS
Final posture code: 122111111111

Subject54
--------------------- ----
Task Element: 1
Command: LOOK
Target Name: Screen
Target Location: -4.00 696.52 1068.7
Result: SUCCESS
Final posture code: 110000000000
--------------------- ----
Task Element: 2
Command: LOOK
Target Name: Slot
Target Location: 140.00 696.52 1005.12
Result: SUCCESS
Final posture code: 110000000000
--------------------- ----
Task Element: 3
Command: REACH
Target Name: Slot
Target Location: 140.00 696.52 1005.12
Result: SUCCESS
Final posture code: 112311221111
--------------------- ----
Task Element: 4
Command: LOOK
Target Name: Dispenser
Target Location: 37.00 696.52 925.094
Result: SUCCESS
Final posture code: 120000000000
--------------------- ----
Task Element: 5
Command: REACH
Target Name: Dispenser
Target Location: 37.00 696.52 925.094
Result: SUCCESS
Final posture code: 122111221111
--------------------- ----
Task Element: 6
Command: LOOK
Target Name: Keys
Target Location: 41.00 592.00 732.2
Result: SUCCESS
Final posture code: 120000000000
--------------------- ----
Task Element: 7
Command: REACH
Target Name: Keys
Target Location: 41.00 592.00 732.2
Result: SUCCESS
Final posture code: 122111111111

Subject97
--------------------- ----
Task Element: 1
Command: LOOK
Target Name: Screen
Target Location: 0.00 0.00 0.00
Result: SUCCESS
Final posture code: 110000000000
--------------------- ----
Task Element: 2
Command: LOOK
Target Name: Slot
Target Location: 140.00 696.52 1005.12
Result: SUCCESS
Final posture code: 110000000000
--------------------- ----
Task Element: 3
Command: REACH
Target Name: Slot
Target Location: 140.00 696.52 1005.12
Result: SUCCESS
Final posture code: 112311221111
--------------------- ----
Task Element: 4
Command: LOOK
Target Name: Dispenser
Target Location: 37.00 696.52 925.094
Result: SUCCESS
Final posture code: 120000000000
--------------------- ----
Task Element: 5
Command: REACH
Target Name: Dispenser
Target Location: 37.00 696.52 925.094
Result: SUCCESS
Final posture code: 122111221111
--------------------- ----
Task Element: 6
Command: LOOK
Target Name: Keys
Target Location: 41.00 592.00 732.2
Result: SUCCESS
Final posture code: 120000000000
--------------------- ----
Task Element: 7
Command: REACH
Target Name: Keys
Target Location: 41.00 592.00 732.2
Result: SUCCESS
Final posture code: 122111111111

Subject98
--------------------- ----
Task Element: 1
Command: LOOK
Target Name: Screen
Target Location: -4.00 696.52 1068.7
Result: SUCCESS
Final posture code: 110000000000
--------------------- ----
Task Element: 2
Command: LOOK
Target Name: Slot
Target Location: 140.00 696.52 1005.12
Result: SUCCESS
Final posture code: 110000000000
--------------------- ----
Task Element: 3
Command: REACH
Target Name: Slot
Target Location: 140.00 696.52 1005.12
Result: SUCCESS
Final posture code: 112311111111
--------------------- ----
Task Element: 4
Command: LOOK

Target Name: Dispenser
Target Location: 37.00 696.52 925.094
Result: SUCCESS
Final posture code: 110000000000
--------------------- ----
Task Element: 5
Command: REACH
Target Name: Dispenser
Target Location: 37.00 696.52 925.094
Result: SUCCESS
Final posture code: 112111111111
--------------------- ----

Task Element: 6
Command: LOOK
Target Name: Keys
Target Location: 41.00 592.00 732.2
Result: SUCCESS
Final posture code: 110000000000
--------------------- ----
Task Element: 7
Command: REACH
Target Name: Keys
Target Location: 41.00 592.00 732.2
Result: SUCCESS
Final posture code: 112111111111

Appendix 2

HADRIAN task analysis results for the kitchen model

Initial HADRIAN evaluation of the kitchen before optimisation

Cooker

! HADRIAN generated results file.
!
! -------------------------------------
! TASK RESULTS
Task: validation
Model:

Subject11
--------------------- ----
Task Element: 1
Command: REACH
Target Name: Cooker
Target Location: 0 -1950 1080
Result: FAILURE
Final posture code: 121111121111

Subject12
--------------------- ----
Task Element: 1
Command: REACH
Target Name: Cooker
Target Location: 0 -1950 1080
Result: FAILURE
Final posture code: 121111121111

Subject27
--------------------- ----
Task Element: 1
Command: REACH
Target Name: Cooker
Target Location: 0 -1950 1080
Result: FAILURE
Final posture code: 121111121111

Subject28
--------------------- ----
Task Element: 1
Command: REACH
Target Name: Cooker
Target Location: 0 -1950 1080
Target Location: -121.05 650.05 1130.01
Result: FAILURE
Final posture code: 121111221111

Subject40
--------------------- ----
Task Element: 1
Command: REACH
Target Name: Cooker
Target Location: 0 -1950 1080
Result: FAILURE
Final posture code: 111171122111

Subject41
--------------------- ----
Task Element: 1
Command: REACH
Target Name: Cooker
Target Location: 0 -1950 1080
Result: FAILURE
Final posture code: 111171122111

Subject47
--------------------- ----
Task Element: 1
Command: REACH
Target Name: Cooker
Target Location: 0 -1950 1080
Result: SUCCESS
Final posture code: 121111121111

Subject54
--------------------- ----
Task Element: 1
Command: REACH
Target Name: Cooker
Target Location: 0 -1950 1080
Result: SUCCESS
Final posture code: 121111121111

Subject97
--------------------- ----
Task Element: 1
Command: REACH
Target Name: Cooker
Target Location: 0 -1950 1080
Result: SUCCESS
Final posture code: 121111121111

Subject98
--------------------- ----
Task Element: 1
Command: REACH
Target Name: Cooker
Target Location: 0 -1950 1080
Result: FAILURE
Final posture code: 121111121111

Oven

! TASK RESULTS
Task: validation

Model:

Subject11
--------------------- ----
Task Element: 1
Command: REACH
Target Name: Oven
Target Location: 440 -1690 600
Result: SUCCESS
Final posture code: 132131221111

Subject12
--------------------- ----
Task Element: 1
Command: REACH
Target Name: Oven
Target Location: 440 -1690 600
760.795Result: SUCCESS
Final posture code: 132121221111

Subject27
--------------------- ----
Task Element: 1
Command: REACH
Target Name: Oven
Target Location: 440 -1690 600
Result: SUCCESS
Final posture code: 132111321111

Subject28
--------------------- ----
Task Element: 1
Command: REACH
Target Name: Oven
Target Location: 440 -1690 600
Result: SUCCESS
Final posture code: 132121321111

Subject40
--------------------- ----
Task Element: 1
Command: REACH
Target Name: Oven
Target Location: 440 -1690 600
Result: FAILURE
Final posture code: 122171122111

Subject41
--------------------- ----
Task Element: 1
Command: REACH
Target Name: Oven
Target Location: 440 -1690 600
Result: FAILURE
Final posture code: 122171122111

Subject47
--------------------- ----
Task Element: 1
Command: REACH
Target Name: Oven
Target Location: 440 -1690 600
Result: SUCCESS
Final posture code: 132141221111

Subject54
--------------------- ----
Task Element: 1
Command: REACH
Target Name: Oven
Target Location: 440 -1690 600
Result: SUCCESS
Final posture code: 132171121111

Subject97
--------------------- ----
Task Element: 1
Command: REACH
Target Name: Oven
Target Location: 440 -1690 600
Result: SUCCESS
Final posture code: 132121221111

Subject98
--------------------- ----
Task Element: 1
Command: REACH
Target Name: Oven
Target Location: 440 -1690 600
Result: SUCCESS
Final posture code: 122121221111

Shelf 1

! TASK RESULTS
Task: validation
Model:

Subject11
--------------------- ----
Task Element: 1
Command: REACH
Target Name: Shelf 1
Target Location: 40 -1120 1800
Result: FAILURE
Final posture code: 112111121111

Subject12
--------------------- ----
Task Element: 1
Command: REACH
Target Name: Shelf 1
Target Location: 40 -1120 1800
Result: FAILURE
Final posture code: 112111121111

Subject27
--------------------- ----
Task Element: 1
Command: REACH
Target Name: Shelf 1
Target Location: 40 -1120 1800
Result: FAILURE
Final posture code: 112111121111

Subject28
-------------------- ----
Task Element: 1
Command: REACH
Target Name: Shelf 1
Target Location: 40 -1120 1800
Result: SUCCESS
Final posture code: 112111121111

Subject40
-------------------- ----
Task Element: 1
Command: REACH
Target Name: Shelf 1
Target Location: 40 -1120 1800
Result: FAILURE
Final posture code: 112571112111

Subject41
-------------------- ----
Task Element: 1
Command: REACH
Target Name: Shelf 1
Target Location: 40 -1120 1800
Result: FAILURE
Final posture code: 112571112111

Subject47

-------------------- ----
Task Element: 1
Command: REACH
Target Name: Shelf 1
Target Location: 40 -1120 1800
Result: SUCCESS
Final posture code: 112111121111

Subject54
-------------------- ----
Task Element: 1
Command: REACH
Target Name: Shelf 1
Target Location: 40 -1120 1800
Result: SUCCESS
Final posture code: 112111111111

Subject97
-------------------- ----
Task Element: 1
Command: REACH
Target Name: Shelf 1
Target Location: 40 -1120 1800
Result: SUCCESS
Final posture code: 112111121111

Subject98
-------------------- ----
Task Element: 1
Command: REACH
Target Name: Shelf 1
Target Location: 40 -1120 1800
Result: FAILURE
Final posture code: 112111111111

Shelf 2

! TASK RESULTS
Task: validation
Model:

Subject11
-------------------- ----
Task Element: 1
Command: REACH
Target Name: Shelf 2
Target Location: 40 -1120 1600
Result: FAILURE
Final posture code: 122111121111

Subject12
-------------------- ----
Task Element: 1
Command: REACH
Target Name: Shelf 2
Target Location: 40 -1120 1600
1258.87Result: SUCCESS
Final posture code: 122111121111

Subject27
-------------------- ----
Task Element: 1
Command: REACH
Target Name: Shelf 2
Target Location: 40 -1120 1600
Result: SUCCESS
Final posture code: 122111121111

Subject28
-------------------- ----
Task Element: 1

Command: REACH
Target Name: Shelf 2
Target Location: 40 -1120 1600
Result: SUCCESS
Final posture code: 122111221111

Subject40
-------------------- ----
Task Element: 1
Command: REACH
Target Name: Shelf 2
Target Location: 40 -1120 1600
Result: FAILURE
Final posture code: 112571112111

Subject41
-------------------- ----
Task Element: 1
Command: REACH
Target Name: Shelf 2
Target Location: 40 -1120 1600
Result: FAILURE
Final posture code: 112171122111

Subject47

-------------------- ----
Task Element: 1
Command: REACH
Target Name: Shelf 2
Target Location: 40 -1120 1600
Result: SUCCESS
Final posture code: 122111121111

Subject54
-------------------- ----
Task Element: 1
Command: REACH
Target Name: Shelf 2
Target Location: 40 -1120 1600
Result: SUCCESS
Final posture code: 122111121111

Subject97
-------------------- ----
Task Element: 1
Command: REACH
Target Name: Shelf 2
Target Location: 40 -1120 1600
Result: SUCCESS
Final posture code: 122111121111

Subject98
-------------------- ----
Task Element: 1
Command: REACH
Target Name: Shelf 2
Target Location: 40 -1120 1600
Result: FAILURE
Final posture code: 112111221111

Sink and Tap

! TASK RESULTS
Task: validation
Model:

Subject11
-------------------- ----
Task Element: 1
Command: REACH
Target Name: Tap
Target Location: 808 -79 1080
Result: SUCCESS
Final posture code: 122111121111
-------------------- ----
Task Element: 2
Command: REACH
Target Name: Sink
Target Location: 620 -440 981
Result: SUCCESS
Final posture code: 121211111111

Subject12
-------------------- ----
Task Element: 1
Command: REACH
Target Name: Tap
Target Location: 808 -79 1080
990.647Result: SUCCESS
Final posture code: 122111111111
-------------------- ----
Task Element: 2
Command: REACH
Target Name: Sink
Target Location: 620 -440 981
Result: SUCCESS
Final posture code: 121211111111

Subject27
-------------------- ----
Task Element: 1
Command: REACH
Target Name: Tap
Target Location: 808 -79 1080
Result: SUCCESS
Final posture code: 122111121111
-------------------- ----
Task Element: 2
Command: REACH
Target Name: Sink
Target Location: 620 -440 981
Result: SUCCESS
Final posture code: 121211121111

Subject28
-------------------- ----
Task Element: 1
Command: REACH
Target Name: Tap
Target Location: 808 -79 1080
Result: SUCCESS
Final posture code: 122111121111
-------------------- ----

Task Element: 2
Command: REACH
Target Name: Sink
Target Location: 620 -440 981
Result: SUCCESS
Final posture code: 121211111111

Subject40
-------------------- ----
Task Element: 1
Command: REACH
Target Name: Tap
Target Location: 808 -79 1080
Result: FAILURE
Final posture code: 112171112111
-------------------- ----
Task Element: 2
Command: REACH
Target Name: Sink
Target Location: 620 -440 981
Result: FAILURE
Final posture code: 111271112111

Subject41
-------------------- ----
Task Element: 1
Command: REACH
Target Name: Tap
Target Location: 808 -79 1080
Result: FAILURE
Final posture code: 112171112111
-------------------- ----
Task Element: 2
Command: REACH
Target Name: Sink
Target Location: 620 -440 981
Result: FAILURE
Final posture code: 111271112111

Subject47
--------------------- ----
Task Element: 1
Command: REACH
Target Name: Tap
Target Location: 808 -79 1080
Result: SUCCESS
Final posture code: 122111121111
--------------------- ----
Task Element: 2
Command: REACH
Target Name: Sink
Target Location: 620 -440 981
Result: SUCCESS
Final posture code: 121211111111

Subject54
--------------------- ----
Task Element: 1
Command: REACH
Target Name: Tap
Target Location: 808 -79 1080
Result: SUCCESS
Final posture code: 122111111111
--------------------- ----
Task Element: 2
Command: REACH
Target Name: Sink
Target Location: 620 -440 981
Result: SUCCESS
Final posture code: 121211111111

Subject97
--------------------- ----
Task Element: 1
Command: REACH
Target Name: Tap
Target Location: 808 -79 1080
Result: SUCCESS
Final posture code: 122111111111
--------------------- ----
Task Element: 2
Command: REACH
Target Name: Sink
Target Location: 620 -440 981
Result: SUCCESS
Final posture code: 121211111111

Subject98
--------------------- ----
Task Element: 1
Command: REACH
Target Name: Tap
Target Location: 808 -79 1080
Result: FAILURE
Final posture code: 122111111111
--------------------- ----
Task Element: 2
Command: REACH
Target Name: Sink
Target Location: 620 -440 981
Result: FAILURE
Final posture code: 021211111111

Work surface

! TASK RESULTS
Task: validation
Model:
Subject11
--------------------- ----
Task Element: 1
Command: REACH
Target Name: Worksurface
Target Location: 0 -1420 1040
Result: SUCCESS
Final posture code: 021111121111

Subject12
--------------------- ----
Task Element: 1
Command: REACH
Target Name: Worksurface
Target Location: 0 -1420 1040
Result: SUCCESS
Final posture code: 021111121111

Subject27
--------------------- ----
Task Element: 1
Command: REACH
Target Name: Worksurface
Target Location: 9.54 -1409.51 978.756
Result: SUCCESS
Final posture code: 021121121111

Subject28
--------------------- ----
Task Element: 1
Command: REACH
Target Name: Worksurface
Target Location: 0 -1420 1040
Result: SUCCESS
Final posture code: 021111121111

Subject40
--------------------- ----
Task Element: 1
Command: REACH
Target Name: Worksurface
Target Location: 0 -1420 1040
Result: FAILURE
Final posture code: 011171112111

Subject41
--------------------- ----
Task Element: 1
Command: REACH
Target Name: Worksurface
Target Location: 0 -1420 1040
Result: FAILURE
Final posture code: 011171112111

Subject47

-------------------- ----
Task Element: 1
Command: REACH
Target Name: Worksurface
Target Location: 0 -1420 1040
Result: SUCCESS
Final posture code: 021111121111

Subject54
-------------------- ----
Task Element: 1
Command: REACH
Target Name: Worksurface
Target Location: 0 -1420 1040
Result: SUCCESS
Final posture code: 021111111111

Subject97
-------------------- ----
Task Element: 1
Command: REACH
Target Name: Worksurface
Target Location: 0 -1420 1040
Result: SUCCESS
Final posture code: 021111111111

Subject98
-------------------- ----
Task Element: 1
Command: REACH
Target Name: Worksurface
Target Location: 0 -1420 1040
Result: SUCCESS
Final posture code: 021111121111

Functions fitted for reach and fit for the 10 subjects

Cooker

$$-898700. + 156.569 x + 576.773 y - 0.0000536048 x y^2 + 126.374 z - 0.000046814 x y z - 3.41023 \times 10^{-9} x^2 y z - 0.0000628647 y^2 z + 3.38045 \times 10^{-8} x y^2 z$$

$$-871189. + 151.675 x + 559.502 y - 0.0000519735 x y^2 + 122.594 z - 0.000045452 x y z - 3.2934 \times 10^{-9} x^2 y z - 0.0000609606 y^2 z + 3.27725 \times 10^{-8} x y^2 z$$

$$-913748. + 164.334 x + 583.366 y - 0.0000569624 x y^2 + 118.271 z - 0.0000446572 x y z - 3.50173 \times 10^{-9} x^2 y z - 0.0000589335 y^2 z + 3.27677 \times 10^{-8} x y^2 z$$

$$-976071. + 170.279 x + 625.596 y - 0.0000582221 x y^2 + 137.034 z - 0.0000506547 x y z - 3.73903 \times 10^{-9} x^2 y z - 0.0000683064 y^2 z + 3.67389 \times 10^{-8} x y^2 z$$

$$-472811. + 65.045 x + 441.806 y - 0.0000561124 x y^2 + 75.9398 z - 0.0000452069 x y z + 1.75 \times 10^{-9} x^2 y z - 0.0000479208 y^2 z + 3.08312 \times 10^{-8} x y^2 z$$

$$-367395. + 48.3978 x + 354.517 y - 0.0000456406 x y^2 + 61.4009 z - 0.0000398323 x y z + 2.44263 \times 10^{-9} x^2 y z - 0.0000324434 y^2 z + 2.33322 \times 10^{-8} x y^2 z$$

$$-822828. + 120.73 x + 639.28 y - 0.0000623805 x y^2 + 131.498 z - 0.0000604231 x y z - 0.0000673658 y^2 z + 3.705 \times 10^{-8} x y^2 z$$

$$-8.77078 \times 10^{6} + 1462.35 x + 6130.38 y - 0.000640558 x y^2 + 1250.4 z - 0.000516693 x y z - 2.1702 \times 10^{-8} x^2 y z - 0.000685954 y^2 z + 3.88228 \times 10^{-7} x y^2 z$$

$$-699977. + 102.037 x + 546.589 y - 0.0000532238 x y^2 + 112.423 z - 0.0000519167 x y z - 0.0000574181 y^2 z + 3.15632 \times 10^{-8} x y^2 z$$

$$-682251. + 118.362 x + 439.601 y - 0.0000406604 x y^2 + 96.4326 z - 0.0000359877 x y z - 2.50292 \times 10^{-9} x^2 y z - 0.0000475538 y^2 z + 2.55701 \times 10^{-8} x y^2 z$$

Oven

$$-598937.+83.5398x+225.813y-0.0000126029xy^2+66.2769z-0.0000138901xyz-0.0000104255y^2z+5.9311\times10^{-9}xy^2z$$

$$-1.21295\times10^{6}+159.766x+454.981y-0.0000180525xy^2+106.863z-0.0000188529xyz-0.0000145426y^2z+5.58991\times10^{-9}xy^2z$$

$$815544.-99.2353x-293.245y+9.8982\times10^{-6}xy^2-59.1348z+7.75285\times10^{-6}xyz+6.80328\times10^{-6}y^2z-1.67046\times10^{-9}xy^2z$$

$$80367.5-16.3764x-50.3387y+8.61408\times10^{-6}xy^2-34.2437z+0.0000107279xyz+8.07075\times10^{-6}y^2z-6.41319\times10^{-9}xy^2z$$

$$322993.-39.3512x-124.247y+4.81372\times10^{-6}xy^2-26.8325z+4.30451\times10^{-6}xyz+4.08452\times10^{-6}y^2z-1.41143\times10^{-9}xy^2z$$

$$46785.6-4.28992x-21.2019y+5.55079\times10^{-7}xy^2-1.37256z+4.21783\times10^{-7}y^2z$$

$$1.06651\times10^{6}-132.559x-404.083y+0.0000165018xy^2-100.463z+0.0000170006xyz+0.0000147258y^2z-5.87577\times10^{-9}xy^2z$$

$$926978.-115.216x-351.217y+0.0000143429xy^2-87.3194z+0.0000147764xyz+0.0000127993y^2z-5.10705\times10^{-9}xy^2z$$

$$945416.-117.508x-358.203y+0.0000146281xy^2-89.0562z+0.0000150703xyz+0.0000130539y^2z-5.20863\times10^{-9}xy^2z$$

$$-572461.+78.4771x+214.822y-0.000011311xy^2+61.0763z-0.0000125065xyz-9.13049\times10^{-6}y^2z+5.02374\times10^{-9}xy^2z$$

Tap

$$-730568.+237.578x+5.7324y-1.02682\times10^{-6}xy^2+0.287195z-3.55137\times10^{-6}xyz+1.07621\times10^{-9}x^2yz+0.000164359y^2z-5.34802\times10^{-8}xy^2z$$

$$-1.17703\times10^{6}+385.501x-3.11423y-5.91285\times10^{-6}xy^2-1.70351z-6.79315\times10^{-6}xyz+2.42125\times10^{-9}x^2yz+0.000271086y^2z-8.5765\times10^{-8}xy^2z$$

$$-1.38186\times10^{6}+449.52x+10.4854y-2.18313\times10^{-6}xy^2+0.276717z-6.40883\times10^{-6}xyz+1.97355\times10^{-9}x^2yz+0.000310439y^2z-1.00931\times10^{-7}xy^2z$$

$$-431102.+142.755x-6.87605y-4.21124\times10^{-6}xy^2-1.93167z-2.10164\times10^{-6}xyz+0.000100421y^2z-3.07085\times10^{-8}xy^2z$$

$$291798. - 49.4667 x - 458.968 y + 0.000105015 x y^2 - 32.6919 z + 0.000042273 x y z - 2.04922 \times 10^{-9} x^2 y z + 0.0000570975 y^2 z - 4.45894 \times 10^{-8} x y^2 z$$

$$-755329. + 104.356 x + 1015.9 y - 0.000293257 x y^2 + 100.508 z - 0.0000989358 x y z + 7.01109 \times 10^{-9} x^2 y z - 0.000179192 y^2 z + 1.55163 \times 10^{-7} x y^2 z$$

$$849864. - 275.376 x - 8.53236 y + 6.71924 \times 10^{-7} x y^2 - 0.879148 z + 5.07257 \times 10^{-6} x y z - 1.53716 \times 10^{-9} x^2 y z - 0.000192593 y^2 z + 6.28841 \times 10^{-8} x y^2 z$$

$$-33416.8 + 10.8646 x + 0.210508 y + 1.33249 \times 10^{-7} x y^2 + 1.07963 z - 3.53754 \times 10^{-6} x y z + 0.0000145731 y^2 z - 4.50565 \times 10^{-9} x y^2 z$$

$$-46697.1 + 14.7135 x + 3.10402 y - 3.67429 \times 10^{-7} x y^2 + 0.414391 z - 2.3931 \times 10^{-6} x y z + 0.0000151823 y^2 z - 4.8884 \times 10^{-9} x y^2 z$$

$$-1.0491 \times 10^{6} + 341.238 x + 5.88331 y - 8.88234 \times 10^{-7} x y^2 + 0.894976 z - 5.13359 \times 10^{-6} x y z + 1.50514 \times 10^{-9} x^2 y z + 0.00023578 y^2 z - 7.66878 \times 10^{-8} x y^2 z$$

Shelf 1

$$1.64221 \times 10^{6} - 301.506 x - 434.786 y + 0.0000206095 x y^2 - 112.468 z + 0.0000289086 x y z - 8.74411 \times 10^{-6} y^2 z - 1.20638 \times 10^{-9} x y^2 z$$

$$-1.49608 \times 10^{6} + 246.769 x + 443.489 y - 0.0000205639 x y^2 + 169.444 z - 0.0000318596 x y z - 0.000014344 y^2 z + 9.30377 \times 10^{-9} x y^2 z$$

$$-749827. + 129.917 x + 214.713 y - 9.80379 \times 10^{-6} x y^2 + 69.8284 z - 0.0000216312 x y z + 1.76469 \times 10^{-9} x^2 y z + 6.82023 \times 10^{-6} y^2 z$$

$$-1.65329 \times 10^{6} + 272.392 x + 490.994 y - 0.0000227941 x y^2 + 187.211 z - 0.0000352952 x y z - 0.0000158301 y^2 z + 1.02869 \times 10^{-8} x y^2 z$$

$$570242. - 80.999 x - 195.646 y + 9.4487 \times 10^{-6} x y^2 - 68.0473 z + 0.0000145225 x y z + 6.03553 \times 10^{-6} y^2 z - 3.97088 \times 10^{-9} x y^2 z$$

$$658854. - 109.45 x - 196.704 y + 9.44892 \times 10^{-6} x y^2 - 60.4955 z + 0.0000141876 x y z + 9.77552 \times 10^{-7} y^2 z - 2.29773 \times 10^{-9} x y^2 z$$

$$2.24663 \times 10^{6} - 354.809 x - 709.104 y + 0.0000340272 x y^2 - 232.704 z + 0.0000469334 x y z + 0.0000191739 y^2 z - 1.30543 \times 10^{-8} x y^2 z$$

$$2.07377 \times 10^{6} - 328.136 x - 653.448 y + 0.0000313645 x y^2 - 214.29 z + 0.0000433792 x y z + 0.0000173451 y^2 z - 1.19404 \times 10^{-8} x y^2 z$$

$$2.04588 \times 10^{6} - 323.743 x - 644.624 y + 0.0000309412 x y^2 - 211.392 z + 0.0000427977 x y z + 0.0000171003 y^2 z - 1.17763 \times 10^{-8} x y^2 z$$

Shelf 2

$$532694.-99.9204\,x-216.152\,y+0.0000119223\,x y^2-48.3963\,z+ \\ 7.46654\times 10^{-6}\,x y z+2.52124\times 10^{-9}\,x^2 y z+0.0000146969\,y^2 z-6.32531\times 10^{-9}\,x y^2 z$$

$$284258.-52.5709\,x-117.841\,y+7.5151\times 10^{-6}\,x y^2-26.4209\,z+ \\ 4.37873\times 10^{-6}\,x y z+1.28177\times 10^{-9}\,x^2 y z+8.6556\times 10^{-6}\,y^2 z-4.12611\times 10^{-9}\,x y^2 z$$

$$-147479.+25.1098\,x+62.3028\,y-2.21937\times 10^{-6}\,x y^2+ \\ 18.8977\,z-4.71861\times 10^{-6}\,x y z-2.63157\times 10^{-6}\,y^2 z$$

$$274273.-63.3863\,x-90.4538\,y+4.38625\times 10^{-6}\,x y^2-9.74012\,z- \\ 6.8666\times 10^{-6}\,x y z+3.65021\times 10^{-9}\,x^2 y z+0.0000116434\,y^2 z-3.59918\times 10^{-9}\,x y^2 z$$

$$-294721.+55.8794\,x+114.732\,y-5.52762\times 10^{-6}\,x y^2+26.9084\,z- \\ 3.26308\times 10^{-6}\,x y z-1.60729\times 10^{-9}\,x^2 y z-7.82983\times 10^{-6}\,y^2 z+3.02429\times 10^{-9}\,x y^2 z$$

$$-179807.+33.7862\,x+69.3636\,y-3.25665\times 10^{-6}\,x y^2+16.8592\,z- \\ 2.12001\times 10^{-6}\,x y z-4.5903\times 10^{-6}\,y^2 z+1.76812\times 10^{-9}\,x y^2 z$$

$$-198827.+36.9651\,x+78.6173\,y-2.53023\times 10^{-6}\,x y^2+21.513\,z- \\ 4.01191\times 10^{-6}\,x y z-4.05752\times 10^{-6}\,y^2 z+1.25094\times 10^{-9}\,x y^2 z$$

$$-200788.+36.9242\,x+79.8614\,y-2.68781\times 10^{-6}\,x y^2+22.139\,z- \\ 4.35613\times 10^{-6}\,x y z-4.01046\times 10^{-6}\,y^2 z+1.30359\times 10^{-9}\,x y^2 z$$

$$-13972.1+0.405733\,x+7.68556\,y+4.21893\times 10^{-7}\,x y^2+ \\ 5.72215\,z-2.41147\times 10^{-6}\,x y z+7.81201\times 10^{-7}\,y^2 z$$

$$-18461.1+4.51855\,x+3.66546\,y+8.28326\times 10^{-7}\,x y^2+ \\ 1.57334\,z+5.97189\times 10^{-7}\,x y z-2.62249\times 10^{-7}\,y^2 z$$

Sink

$$-523738.+85.5854\,x+240.116\,y-0.0000135733\,x y^2+63.1442\,z- \\ 0.0000183362\,x y z-0.0000107624\,y^2 z+5.77527\times 10^{-9}\,x y^2 z$$

$$-477292.+78.0969\,x+218.697\,y-0.0000123141\,x y^2+ \\ 57.464\,z-0.0000166555\,x y z-9.7963\times 10^{-6}\,y^2 z+5.23218\times 10^{-9}\,x y^2 z$$

$$-43896.4+9.1115\,x+17.7414\,y-7.62828\times 10^{-8}\,x y^2+ \\ 3.75523\,z-4.94178\times 10^{-7}\,x y z-6.79357\times 10^{-7}\,y^2 z$$

$$-1.49708\times 10^{6}+269.62\,x+620.879\,y-0.0000359957\,x y^{2}+160.377\,z-0.0000358418\,x y z-4.13461\times 10^{-9}\,x^{2} y z-0.0000361524\,y^{2} z+1.79531\times 10^{-8}\,x y^{2} z$$

$$-1.52704\times 10^{6}+272.595\,x+638.185\,y-0.0000345863\,x y^{2}+161.78\,z-0.000037408\,x y z-3.73723\times 10^{-9}\,x^{2} y z-0.000033464\,y^{2} z+1.59044\times 10^{-8}\,x y^{2} z$$

$$-75564.1+14.2052\,x+32.3598\,y-9.41431\times 10^{-7}\,x y^{2}+7.63759\,z-1.64653\times 10^{-6}\,x y z-1.33943\times 10^{-6}\,y^{2} z$$

$$-272211.+43.4705\,x+126.044\,y-7.60889\times 10^{-6}\,x y^{2}+33.6216\,z-0.0000100746\,x y z-5.70998\times 10^{-6}\,y^{2} z+3.3104\times 10^{-9}\,x y^{2} z$$

$$-162013.+27.6839\,x+72.7905\,y-3.53676\times 10^{-6}\,x y^{2}+18.5742\,z-5.02177\times 10^{-6}\,x y z-3.19034\times 10^{-6}\,y^{2} z+1.41775\times 10^{-9}\,x y^{2} z$$

$$429989.-78.9586\,x-174.235\,y+9.95254\times 10^{-6}\,x y^{2}-40.5835\,z+7.58474\times 10^{-6}\,x y z+1.55291\times 10^{-9}\,x^{2} y z+0.0000106693\,y^{2} z-4.90838\times 10^{-9}\,x y^{2} z$$

Work surface

$$-1.32158\times 10^{6}+176.793\,x+720.919\,y-0.0000529245\,x y^{2}+182.735\,z-0.000057358\,x y z-0.0000494269\,y^{2} z+2.8144\times 10^{-8}\,x y^{2} z$$

$$-1.1454\times 10^{6}+151.244\,x+627.772\,y-0.0000458268\,x y^{2}+159.402\,z-0.0000499711\,x y z-0.0000432173\,y^{2} z+2.44569\times 10^{-8}\,x y^{2} z$$

$$-628141.+82.6339\,x+350.996\,y-0.0000260874\,x y^{2}+87.8551\,z-0.0000295541\,x y z-0.0000221808\,y^{2} z+1.31452\times 10^{-8}\,x y^{2} z$$

$$-942974.+119.788\,x+523.968\,y-0.0000377341\,x y^{2}+133.777\,z-0.000041807\,x y z-0.0000365805\,y^{2} z+2.03818\times 10^{-8}\,x y^{2} z$$

$$2.34434\times 10^{6}-375.926\,x-1194.56\,y+0.0000960659\,x y^{2}-292.584\,z+0.0000978203\,x y z+0.0000717345\,y^{2} z-4.67398\times 10^{-8}\,x y^{2} z$$

$$1.09818\times 10^{7}-1619.57\,x-5773.19\,y+0.000445226\,x y^{2}-1436.65\,z+0.000457247\,x y z-3.18915\times 10^{-9}\,x^{2} y z+0.000381865\,y^{2} z-2.2953\times 10^{-7}\,x y^{2} z$$

$$124097.-33.3578\,x-39.421\,y+4.69834\times 10^{-6}\,x y^{2}-8.22086\,z+1.94348\times 10^{-6}\,x y z+2.30476\times 10^{-6}\,y^{2} z-2.18147\times 10^{-9}\,x y^{2} z$$

$$204480.-44.9241\,x-83.1951\,y+8.15203\times 10^{-6}\,x y^{2}-19.0466\,z+5.74807\times 10^{-6}\,x y z+4.90826\times 10^{-6}\,y^{2} z-3.85774\times 10^{-9}\,x y^{2} z$$

$$214193.-46.1997\,x-88.6118\,y+8.55755\times 10^{-6}\,x y^{2}-20.4072\,z+6.2056\times 10^{-6}\,x y z+5.25196\times 10^{-6}\,y^{2} z-4.06296\times 10^{-9}\,x y^{2} z$$

$$- 4.99164 \times 10^{6} + 729.408\,x + 2633.55\,y - 0.000200708\,x y^{2} + 657.231\,z - 0.000209182\,x y z + 1.75449 \times 10^{-9} x^{2} y z - 0.000172925\,y^{2} z + 1.03151 \times 10^{-7} x y^{2} z$$

HADRIAN results for Validation after optimisation

Cooker

! HADRIAN generated results file.
!
! -------------------------------------
! TASK RESULTS
Task: validation
Model:

Subject11
--------------------- ----
Task Element: 1
Command: REACH
Target Name: Cooker
Target Location: 0 -1950 1120.8
Result: SUCCESS
Final posture code: 121111121111

Subject12
--------------------- ----
Task Element: 1
Command: REACH
Target Name: Cooker
Target Location: 0 -1950 1120.8

Result: SUCCESS
Final posture code: 121111121111

Subject27
--------------------- ----
Task Element: 1
Command: REACH
Target Name: Cooker
Target Location: 0 -1950 1120.8
Result: SUCCESS
Final posture code: 121111121111

Subject28
--------------------- ----
Task Element: 1
Command: REACH
Target Name: Cooker
Target Location: 0 -1950 1120.8

Target Location: -121.05 650.05 1130.01
Result: SUCCESS
Final posture code: 121111221111

Subject40
--------------------- ----
Task Element: 1
Command: REACH
Target Name: Cooker
Target Location: 0 -1950 1120.8

Result: SUCCESS
Final posture code: 111171122111

Subject41

--------------------- ----
Task Element: 1
Command: REACH
Target Name: Cooker
Target Location: 0 -1950 1120.8
Result: SUCCESS
Final posture code: 111171122111

Subject47
--------------------- ----
Task Element: 1
Command: REACH
Target Name: Cooker
Target Location: 0 -1950 1120.8
Result: SUCCESS
Final posture code: 121111121111

Subject54
--------------------- ----
Task Element: 1
Command: REACH
Target Name: Cooker
Target Location: 0 -1950 1120.8
Result: SUCCESS
Final posture code: 121111121111

Subject97
--------------------- ----
Task Element: 1
Command: REACH
Target Name: Cooker
Target Location: 0 -1950 1120.8
Result: SUCCESS
Final posture code: 121111121111

Subject98
--------------------- ----
Task Element: 1
Command: REACH
Target Name: Cooker
Target Location: 0 -1950 1120.8
Result: SUCCESS
Subject location: 0.00 0.00 0.00
Subject orientation: 0.00 0.00 -170.79
Final posture code: 121111121111

Oven

! TASK RESULTS
Task: validation
Model:

Subject11
-------------------- ----
Task Element: 1
Command: REACH
Target Name: Oven
Target Location: 440 -1690 760.795
Result: SUCCESS
Final posture code: 132131221111

Subject12
-------------------- ----
Task Element: 1
Command: REACH
Target Name: Oven
Target Location: 440 -1690 760.795
760.795Result: SUCCESS
Final posture code: 132121221111

Subject27
-------------------- ----
Task Element: 1
Command: REACH
Target Name: Oven
Target Location: 440 -1690 760.795
Result: SUCCESS
Final posture code: 132111321111

Subject28
-------------------- ----
Task Element: 1
Command: REACH
Target Name: Oven
Target Location: 440 -1690 760.795
Result: SUCCESS
Final posture code: 132121321111

Subject40
-------------------- ----
Task Element: 1
Command: REACH
Target Name: Oven
Target Location: 440 -1690 760.795
Result: SUCCESS
Final posture code: 122171122111

Subject41
-------------------- ----
Task Element: 1
Command: REACH
Target Name: Oven
Target Location: 440 -1690 760.795
Result: SUCCESS
Final posture code: 122171122111

Subject47
-------------------- ----
Task Element: 1
Command: REACH
Target Name: Oven
Target Location: 440 -1690 760.795
Result: SUCCESS
Final posture code: 132141221111

Subject54
-------------------- ----
Task Element: 1
Command: REACH
Target Name: Oven
Target Location: 440 -1690 760.795
Result: SUCCESS
Final posture code: 132171121111

Subject97
-------------------- ----
Task Element: 1
Command: REACH
Target Name: Oven
Target Location: 440 -1690 760.795
Result: SUCCESS
Final posture code: 132121221111

Subject98
-------------------- ----
Task Element: 1
Command: REACH
Target Name: Oven
Target Location: 440 -1690 760.795
Result: SUCCESS
Final posture code: 122121221111

Shelf 1

! TASK RESULTS
Task: validation
Model:

Subject11
-------------------- ----
Task Element: 1
Command: REACH
Target Name: Shelf 1
Target Location: 40 -1039.97 1458.87
Result: SUCCESS
Final posture code: 112111121111

Subject12
-------------------- ----
Task Element: 1
Command: REACH
Target Name: Shelf 1
Target Location: 40 -1039.97 1458.87
Result: SUCCESS
Final posture code: 112111121111

Subject27
-------------------- ----
Task Element: 1
Command: REACH
Target Name: Shelf 1
Target Location: 40 -1039.97 1458.87
Result: SUCCESS
Final posture code: 112111121111

Subject28
-------------------- ----
Task Element: 1
Command: REACH
Target Name: Shelf 1
Target Location: 40 -1039.97 1458.87
Result: SUCCESS
Final posture code: 112111121111

Subject40
-------------------- ----
Task Element: 1
Command: REACH

Target Name: Shelf 1
Target Location: 40 -1039.97 1458.87
Result: FAILURE
Failure distance: 79.14
Final posture code: 112571112111

Subject41
--------------------- ----
Task Element: 1
Command: REACH
Target Name: Shelf 1
Target Location: 40 -1039.97 1458.87
Result: FAILURE
Failure distance: 17.98
Final posture code: 112571112111

Subject47
--------------------- ----
Task Element: 1
Command: REACH
Target Name: Shelf 1
Target Location: 40 -1039.97 1458.87
Result: SUCCESS
Final posture code: 112111121111

Subject54
--------------------- ----
Task Element: 1
Command: REACH
Target Name: Shelf 1
Target Location: 40 -1039.97 1458.87
Result: SUCCESS
Final posture code: 112111111111

Subject97
--------------------- ----
Task Element: 1
Command: REACH
Target Name: Shelf 1
Target Location: 40 -1039.97 1458.87
Result: SUCCESS
Final posture code: 112111121111

Subject98
--------------------- ----
Task Element: 1
Command: REACH
Target Name: Shelf 1
Target Location: 40 -1039.97 1458.87
Result: FAILURE
Failure distance: 138.66
Final posture code: 112111111111

Shelf 2

! TASK RESULTS
Task: validation
Model:

Subject11
--------------------- ----
Task Element: 1
Command: REACH
Target Name: Shelf 2
Target Location: 40 -1143.97 1258.87
Result: SUCCESS
Final posture code: 122111121111

Subject12
--------------------- ----
Task Element: 1
Command: REACH
Target Name: Shelf 2
Target Location: 40 -1143.97 1258.87
1258.87Result: SUCCESS
Final posture code: 122111121111

Subject27
--------------------- ----
Task Element: 1
Command: REACH
Target Name: Shelf 2
Target Location: 40 -1143.97 1258.87
Result: SUCCESS
Final posture code: 122111121111

Subject28
--------------------- ----
Task Element: 1
Command: REACH
Target Name: Shelf 2
Target Location: 40 -1143.97 1258.87
Result: SUCCESS
Final posture code: 122111221111

Subject40
--------------------- ----
Task Element: 1
Command: REACH
Target Name: Shelf 2
Target Location: 40 -1143.97 1258.87
Result: SUCCESS
Final posture code: 112571112111

Subject41
--------------------- ----
Task Element: 1
Command: REACH
Target Name: Shelf 2
Target Location: 40 -1143.97 1258.87
Result: SUCCESS
Final posture code: 112171122111

Subject47
--------------------- ----
Task Element: 1
Command: REACH
Target Name: Shelf 2
Target Location: 40 -1143.97 1258.87
Result: SUCCESS
Final posture code: 122111121111

Subject54
--------------------- ----
Task Element: 1
Command: REACH
Target Name: Shelf 2
Target Location: 40 -1143.97 1258.87
Result: SUCCESS
Final posture code: 122111121111

Subject97
--------------------- ----
Task Element: 1
Command: REACH
Target Name: Shelf 2
Target Location: 40 -1143.97 1258.87
Result: SUCCESS
Final posture code: 122111121111
Subject98

--------------------- ----
Task Element: 1
Command: REACH
Target Name: Shelf 2
Target Location: 40 -1143.97 1258.87
Result: SUCCESS
Final posture code: 112111221111

Sink and Tap

! TASK RESULTS
Task: validation
Model:

Subject11
--------------------- ----
Task Element: 1
Command: REACH
Target Name: Tap
Target Location: 797.165 -152.62 990.647
Result: SUCCESS
Final posture code: 122111121111
--------------------- ----
Task Element: 2
Command: REACH
Target Name: Sink
Target Location: 414.1 -426.72 890.647
Result: SUCCESS
Final posture code: 121211111111

Subject12
--------------------- ----
Task Element: 1
Command: REACH
Target Name: Tap
Target Location: 797.165 -152.62 990.647
990.647Result: SUCCESS
Final posture code: 122111111111
--------------------- ----
Task Element: 2
Command: REACH
Target Name: Sink
Target Location: 414.1 -426.72 890.647
Result: SUCCESS
Final posture code: 121211111111

Subject27
--------------------- ----
Task Element: 1
Command: REACH
Target Name: Tap
Target Location: 797.165 -152.62 990.647
Result: SUCCESS
Final posture code: 122111121111
--------------------- ----
Task Element: 2
Command: REACH
Target Name: Sink
Target Location: 414.1 -426.72 890.647
Result: SUCCESS
Final posture code: 121211121111

Subject28
--------------------- ----
Task Element: 1
Command: REACH
Target Name: Tap
Target Location: 797.165 -152.62 990.647
Result: SUCCESS
Final posture code: 122111121111
--------------------- ----
Task Element: 2
Command: REACH
Target Name: Sink
Target Location: 414.1 -426.72 890.647
Result: SUCCESS
Final posture code: 121211111111

Subject40
--------------------- ----
Task Element: 1
Command: REACH
Target Name: Tap
Target Location: 797.165 -152.62 990.647
Result: SUCCESS
Final posture code: 112171112111
--------------------- ----
Task Element: 2
Command: REACH
Target Name: Sink
Target Location: 414.1 -426.72 890.647
Result: SUCCESS
Final posture code: 111271112111

Subject41
--------------------- ----
Task Element: 1
Command: REACH
Target Name: Tap
Target Location: 797.165 -152.62 990.647
Result: SUCCESS
Final posture code: 112171112111
--------------------- ----
Task Element: 2
Command: REACH
Target Name: Sink
Target Location: 414.1 -426.72 890.647
Result: SUCCESS
Final posture code: 111271112111

Subject47
--------------------- ----
Task Element: 1
Command: REACH
Target Name: Tap
Target Location: 797.165 -152.62 990.647
Result: SUCCESS
Final posture code: 122111121111
--------------------- ----
Task Element: 2
Command: REACH
Target Name: Sink
Target Location: 414.1 -426.72 890.647
Result: SUCCESS
Final posture code: 121211111111

Subject54
--------------------- ----
Task Element: 1
Command: REACH
Target Name: Tap
Target Location: 797.165 -152.62 990.647
Result: SUCCESS
Final posture code: 122111111111
--------------------- ----
Task Element: 2
Command: REACH
Target Name: Sink
Target Location: 414.1 -426.72 890.647

Result: SUCCESS
Final posture code: 121211111111

Subject97

--------------------- ----
Task Element: 1
Command: REACH
Target Name: Tap
Target Location: 797.165 -152.62 990.647
Result: SUCCESS
Final posture code: 122111111111
--------------------- ----
Task Element: 2
Command: REACH
Target Name: Sink
Target Location: 414.1 -426.72 890.647
Result: SUCCESS
Final posture code: 121211111111

Subject98

--------------------- ----
Task Element: 1
Command: REACH
Target Name: Tap
Target Location: 797.165 -152.62 990.647
Result: SUCCESS
Final posture code: 122111111111
--------------------- ----
Task Element: 2
Command: REACH
Target Name: Sink
Target Location: 414.1 -426.72 890.647
Result: SUCCESS
Final posture code: 021211111111

Work surface

! TASK RESULTS
Task: validation
Model:

Subject11

--------------------- ----
Task Element: 1
Command: REACH
Target Name: Worksurface
Target Location: 9.54 -1409.51 978.756
Result: SUCCESS
Final posture code: 021111121111

Subject12

--------------------- ----
Task Element: 1
Command: REACH
Target Name: Worksurface
Target Location: 9.54 -1409.51 978.756
Result: SUCCESS
Final posture code: 021111121111

Subject27

--------------------- ----
Task Element: 1
Command: REACH
Target Name: Worksurface
Target Location: 9.54 -1409.51 978.756
Result: SUCCESS
Final posture code: 021121121111

Subject28

--------------------- ----
Task Element: 1
Command: REACH
Target Name: Worksurface
Target Location: 9.54 -1409.51 978.756
Result: SUCCESS
Final posture code: 021111121111

Subject40

--------------------- ----
Task Element: 1
Command: REACH
Target Name: Worksurface
Target Location: 9.54 -1409.51 978.756
Result: SUCCESS
Final posture code: 011171112111

Subject41

--------------------- ----
Task Element: 1
Command: REACH
Target Name: Worksurface
Target Location: 9.54 -1409.51 978.756
Result: SUCCESS
Final posture code: 011171112111

Subject47

--------------------- ----
Task Element: 1
Command: REACH
Target Name: Worksurface
Target Location: 9.54 -1409.51 978.756
Result: SUCCESS
Final posture code: 021111121111

Subject54

--------------------- ----
Task Element: 1
Command: REACH

Target Name: Worksurface
Target Location: 9.54 -1409.51 978.756
Result: SUCCESS
Final posture code: 021111111111

Subject97

--------------------- ----
Task Element: 1
Command: REACH
Target Name: Worksurface
Target Location: 9.54 -1409.51 978.756
Result: SUCCESS
Final posture code: 021111111111

Subject98

--------------------- ----
Task Element: 1
Command: REACH
Target Name: Worksurface
Target Location: 9.54 -1409.51 978.756
Result: SUCCESS
Final posture code: 0211111